Sleep Inertia Project: Progress Report ver. 1.1α

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1 Introduction

The aim of the report is to show novel methods in functional neuroimaging [1] of sleep inertia stages with emphasis on novel time-frequency preprocessing meth-

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14. ABSTRACT
The aim of the report is to show novel methods in functional neuroimaging of sleep inertia stages with emphasis on novel time-frequency preprocessing methods and models of effective connectivity evaluated by dynamic causal modeling and econometric models (such as Granger causality and related methods).

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ods [2, 3, 4, 5, 6] and models of effective connectivity evaluated by dynamic causal modeling and econometric models (such as Granger causality and related methods) [7, 8, 1]

2 Methods

The EEG signals from two conditions #1 and #2 for all experimental factors $EEG08$ till $EEG17$ for the following channels: $C4 - A1$; $C3 - A2$; $Fz - A1$; $Pz - A1$; $Oz - A2$ where first preprocessed with EMD adaptive filtering procedures (removing mostly muscle artifacts in lower and high frequency ranges). The so obtained *clean EEG* signals were further with interdependence measures.

2.1 Empirical Mode Decomposition (EMD) EEG Preprocessing

...to be added soon...

2.2 Signals Interdependence Evaluation

Suppose that we are given n signals $X_1(k), X_2(k), \ldots, X_n(k)$, each stemming from a different channel. We consider the multivariate autoregressive (MVAR) model:

$$X(k) = \sum_{l=1}^{p} \mathbf{A}(j)X(k-l) + E(k), \tag{1}$$

where $X(k) \triangleq (X_1(k), X_2(k), \ldots, X_n(k))^T$, p is the model order, the model coefficients $\mathbf{A}(j)$ are $n \times n$ matrices, and $E(k)$ is a zero-mean Gaussian random vector of size n. In words: Each signal $X_i(k)$ is assumed to linearly depend on its own p past values and the p past values of the other signals $X_j(k)$. The deviation between $X(k)$ and this linear dependence is modeled by the noise component $E(k)$. Model (1) can also be cast in the form:

$$E(k) = \sum_{l=0}^{p} \tilde{\mathbf{A}}(j)X(k-l), \tag{2}$$

where $\tilde{\mathbf{A}}(0) = \mathbf{I}$ (identity matrix) and $\tilde{\mathbf{A}}(j) \triangleq -\mathbf{A}(j)$ for $j > 0$. One can transform (2) into the frequency domain (by applying the z-transform and by substituting $z \triangleq e^{-2\pi i \Delta t}$, where $1/\Delta t$ is the sampling rate):

$$X(f) = \tilde{\mathbf{A}}^{-1}(f)E(f) \triangleq \mathbf{H}(f)E(f). \tag{3}$$

The power spectrum matrix of the signal $X(k)$ is determined as

$$\mathbf{S}(f) \triangleq X(f)X(f)^* = \mathbf{H}(f)\mathbf{V}\mathbf{H}(f), \tag{4}$$

where $\mathbf{V}$ stands for the covariance matrix of $E(k)$.

2.2.1 Coherence (COH)

The coherence function quantifies linear correlations in frequency domain. One distinguishes the magnitude square coherence function and the phase coherence function. The former is dened as:

$$c(f) \triangleq \frac{|X(f)Y^*(f)|^2}{|X(f)|\,|Y(f)|}, \tag{5}$$

where $X(f)$ and $Y(f)$ are the Fourier transforms of x and y respectively; Y^* is the complex conjugate of $Y \in \mathbb{C}$, and $|Y|$ is the magnitude of Y . The phase coherence function is dened as

$$\phi(f) \triangleq \arg[X(f)Y^*(f)]. \tag{6}$$

In practice, one often subdivides the signals x and y in M segments (of equal length), and determines $c(f)$ by averaging over those segments:

$$c(f) \triangleq \frac{|\langle X(f)Y^*(f)\rangle|^2}{|\langle X(f)\rangle|\,|\langle Y(f)\rangle|}, \tag{7}$$

where $\langle\cdot\rangle$ denotes averaging over the M segments. Along the same lines, the phase coherence $\phi(f)$ is often computed as:

$$\phi(f) \triangleq \arg[\langle X(f)Y^*(f)\rangle]. \tag{8}$$

Note that both $c(f)$ and $\phi(f)$ depend on the frequency f.

As for properties of coherence, its estimated value ranges between 0 and 1. For a given frequency. A value of 0 indicates that the activities of the signals in this particular frequency bin are linearly independent, whereas a maximum value of 1 gives the top linear correlation for such particular frequency bin.

2.2.2 Directed Transfer Function (DTF)

$$\gamma_{ij}^2(f) \triangleq \frac{|H_{ij}(f)|^2}{\sum_{j=1}^{m} |H_{ij}(f)|^2} \in [0,1], \tag{9}$$

where the (frequency-dependent) normalization is chosen so that $\gamma_{ij}^2(f)$ quanties the fraction of inow to channel i stemming from channel j.

2.2.3 Partial Directed Coherence (PDC)

$$P_{ij}(f) \triangleq \frac{\tilde{A}_{ij}(f)}{\sqrt{\sum_{i=1}^{m} \left|\tilde{A}_{ij}(f)\right|^2}} \in \mathbb{C}, \tag{10}$$

2.2.4 Direct Directed Transfer Function (dDTF)

$$\chi_{ij}^2(f) \triangleq F_{ij}^2(f) C_{ij}^2(f) \in [0,1], \tag{11}$$

which is non-zero if the connection between channel i and j is causal (non-zero $F_{ij}^2(f)$) and direct (non-zero $C_{ij}^2(f)$).

3 Preliminary pairwise channel synchrony evaluation results

3.1 Magnitude coherence

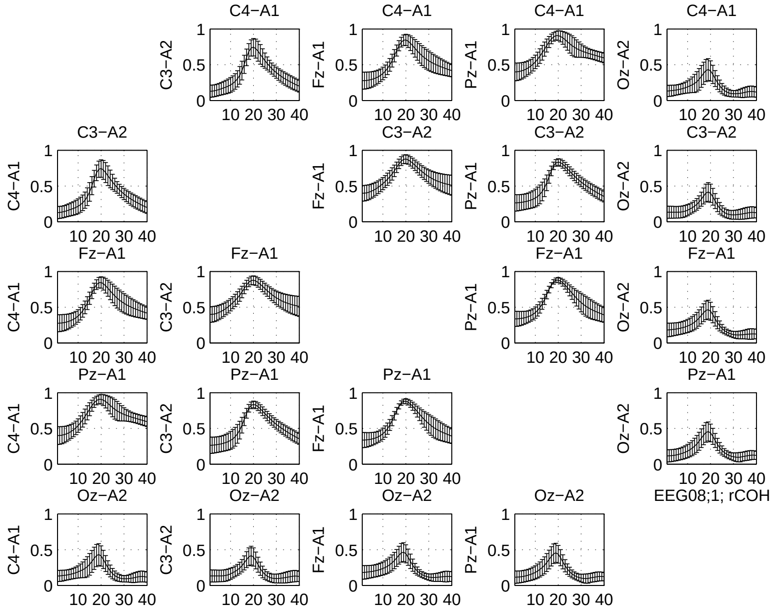

Figure 1: Magnitude coherence as in (5): Condition #1 & factor EEG08. *X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

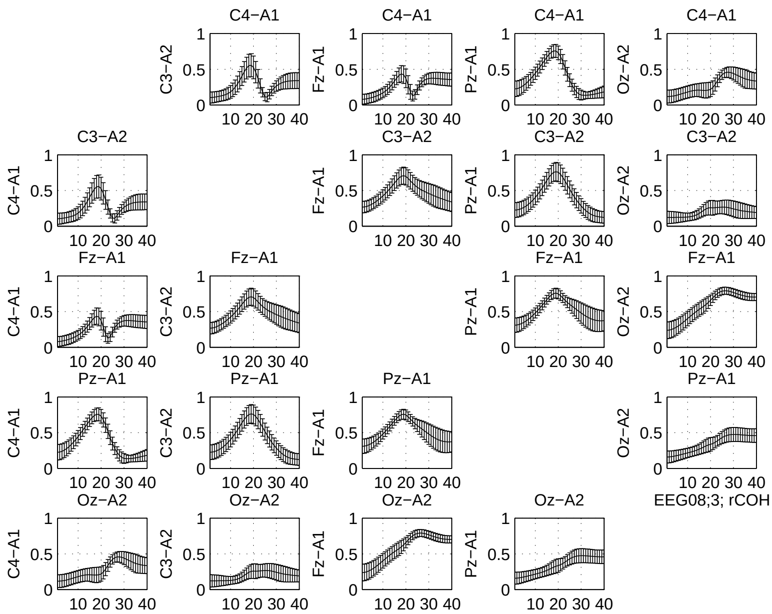

Figure 2: Magnitude coherence as in (5): Condition #3 & factor EEG08. *X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

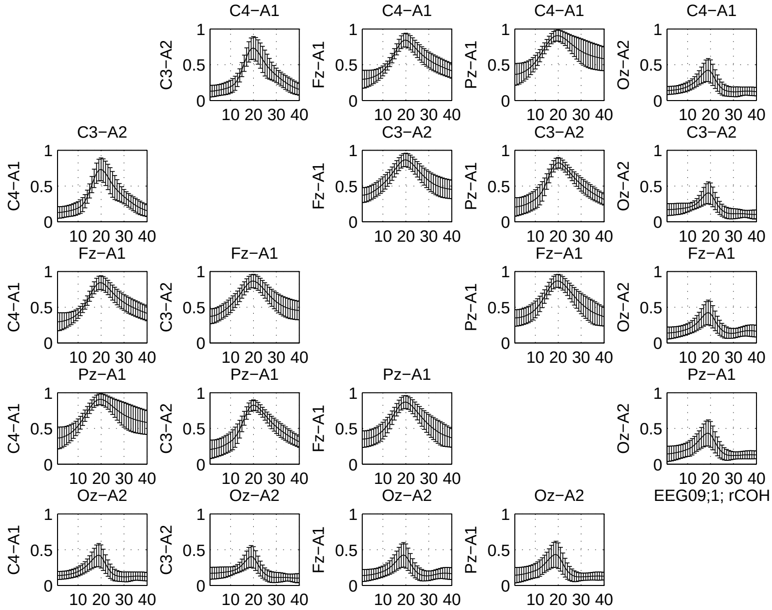

Figure 3: Magnitude coherence as in (5): Condition #1 & factor EEG09. *X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

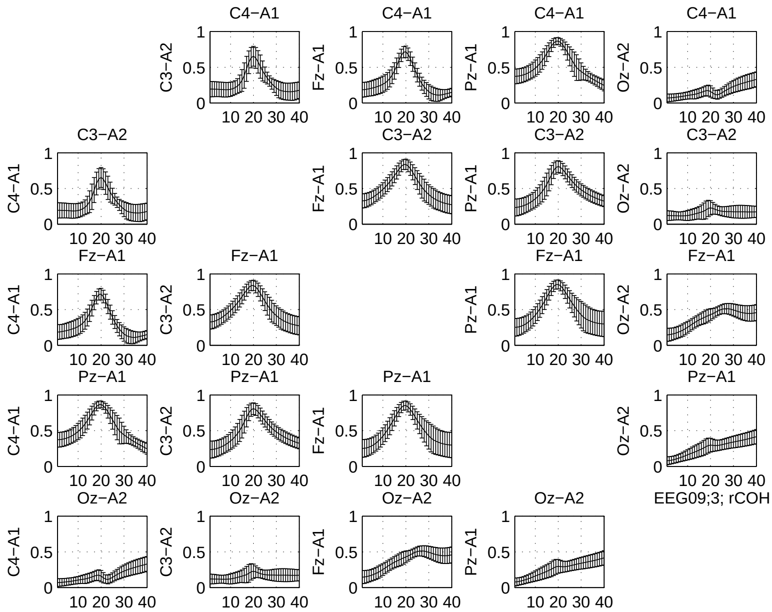

Figure 4: Magnitude coherence as in (5): Condition #3 & factor EEG09.*X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

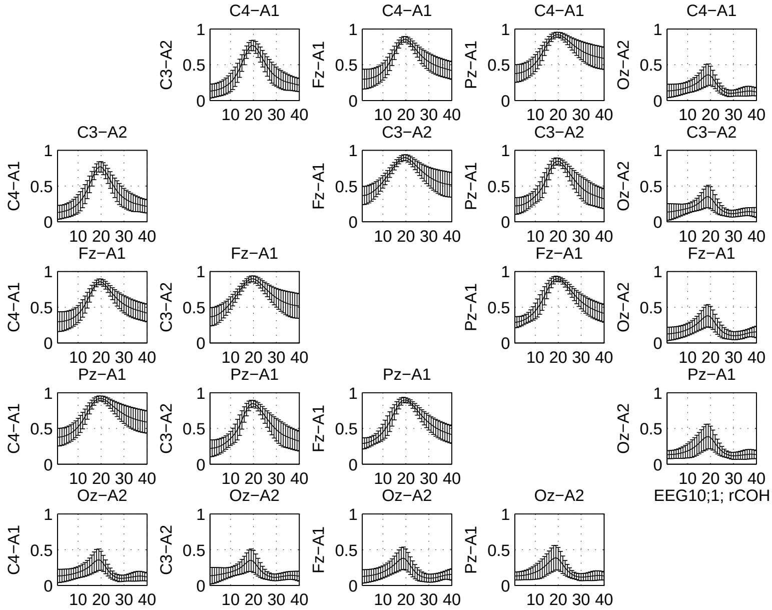

Figure 5: Magnitude coherence as in (5): Condition #1 & factor EEG10.*X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

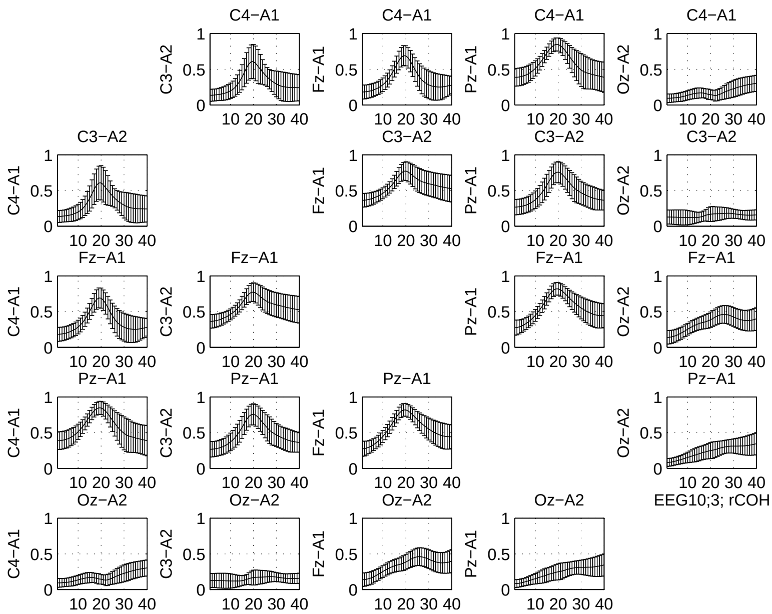

Figure 6: Magnitude coherence as in (5): Condition #3 & factor EEG10.*X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

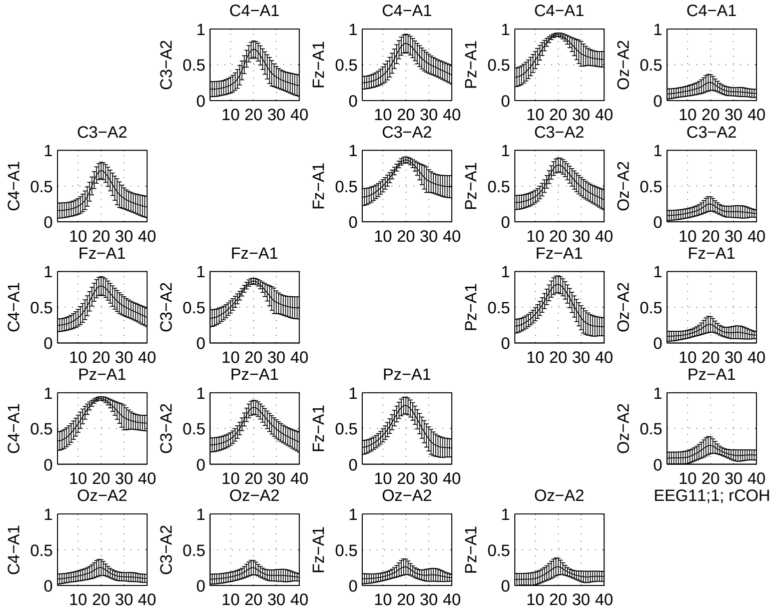

Figure 7: Magnitude coherence as in (5): Condition #1 & factor EEG11.*X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

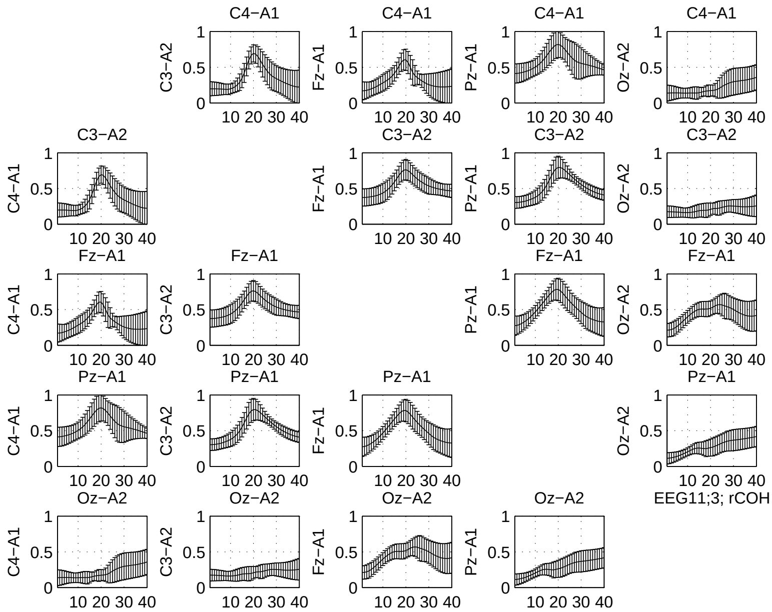

Figure 8: Magnitude coherence as in (5): Condition #3 & factor EEG11.*X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

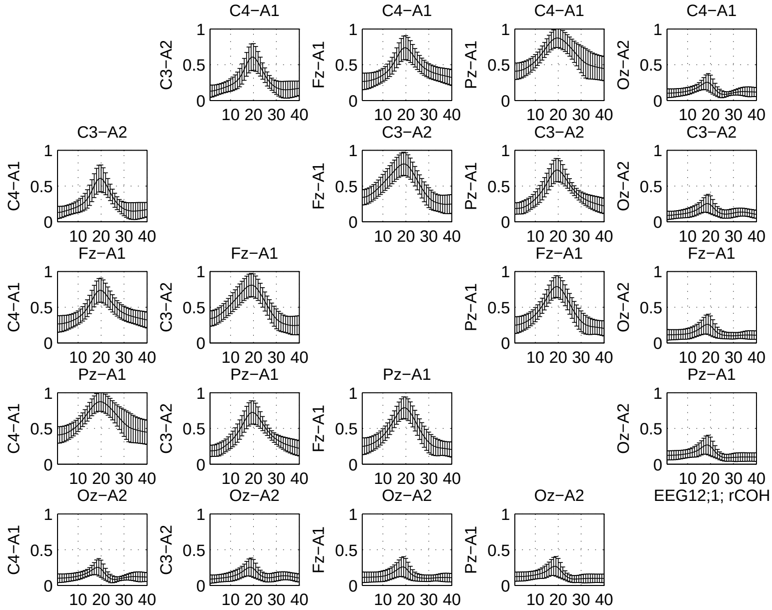

Figure 9: Magnitude coherence as in (5): as in (5): Condition #1 & factor EEG12.*X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

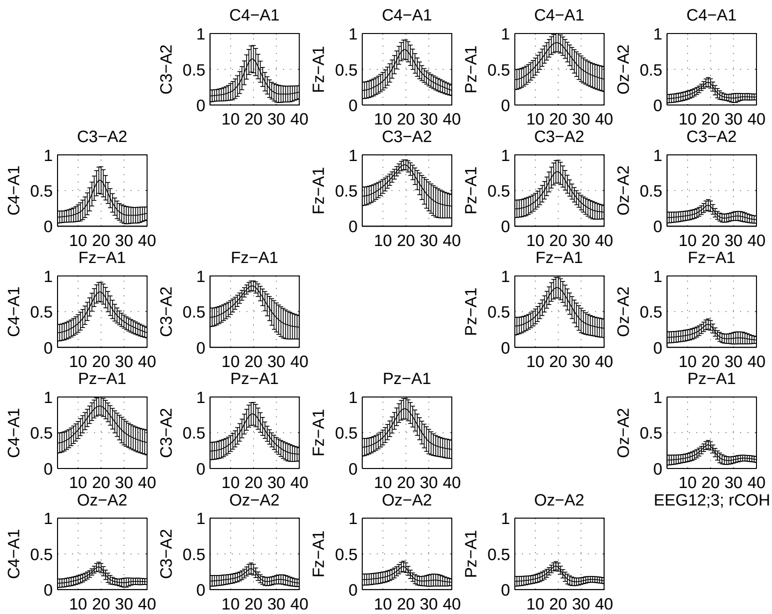

Figure 10: Magnitude coherence as in (5): Condition #3 & factor EEG12.*X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

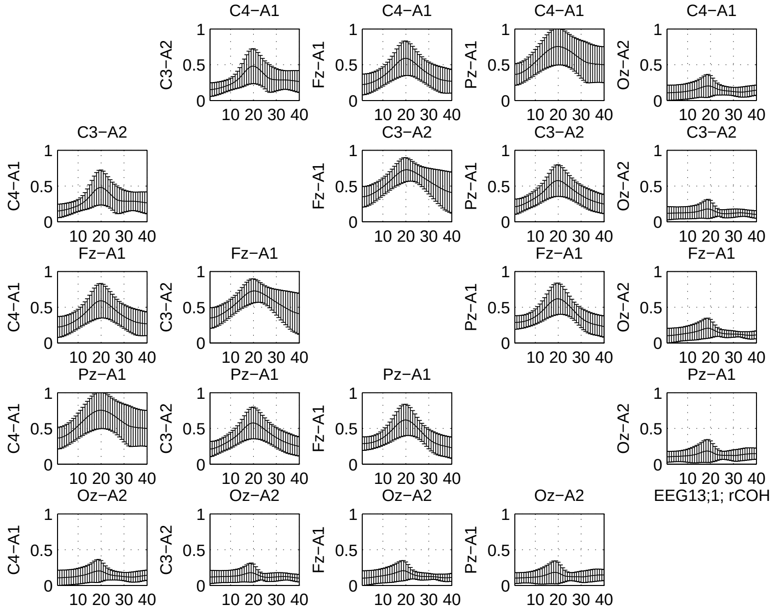

Figure 11: Magnitude coherence as in (5): Condition #1 & factor EEG13.*X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

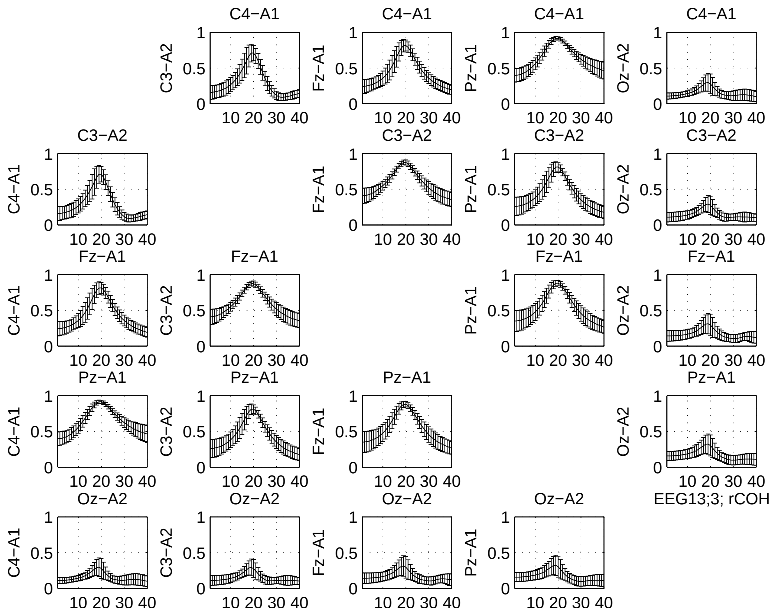

Figure 12: Magnitude coherence as in (5): Condition #3 & factor EEG13.*X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

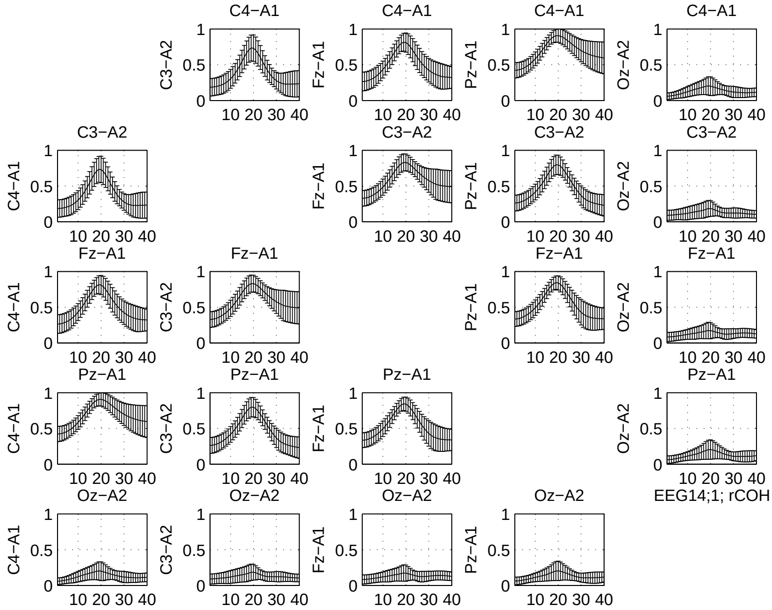

Figure 13: Magnitude coherence as in (5): Condition #1 & factor EEG14.*X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

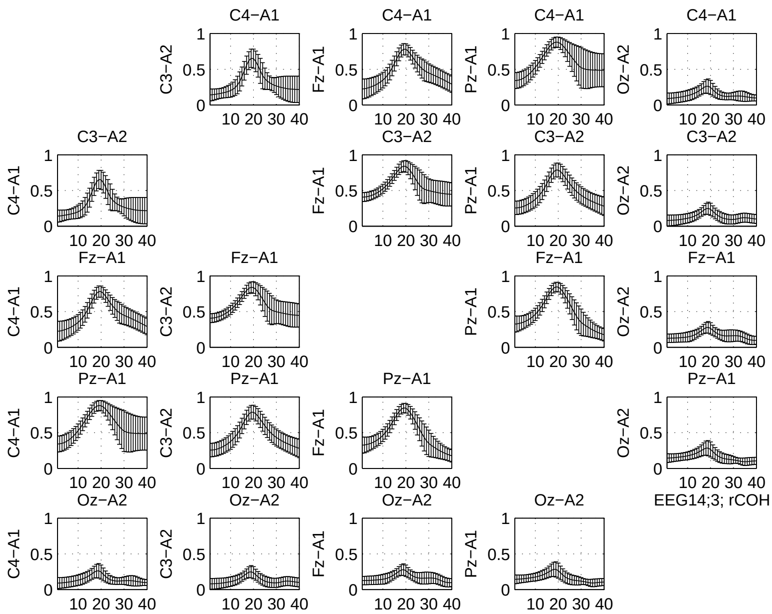

Figure 14: Magnitude coherence as in (5): Condition #3 & factor EEG14.*X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

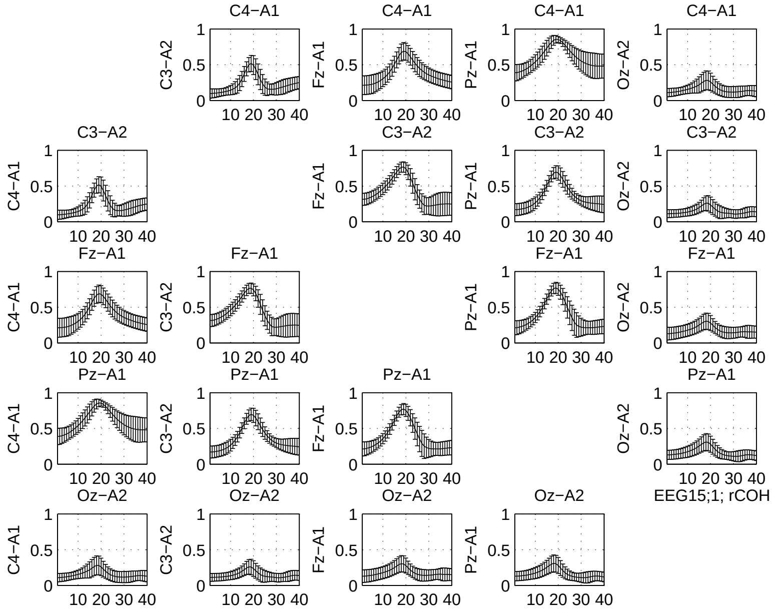

Figure 15: Magnitude coherence as in (5): Condition #1 & factor EEG15.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

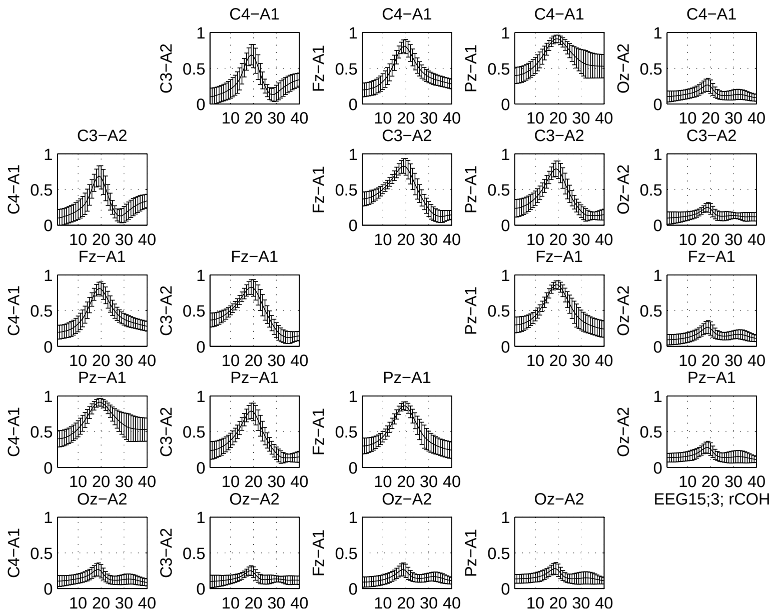

Figure 16: Magnitude coherence as in (5): Condition #3 & factor EEG15.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

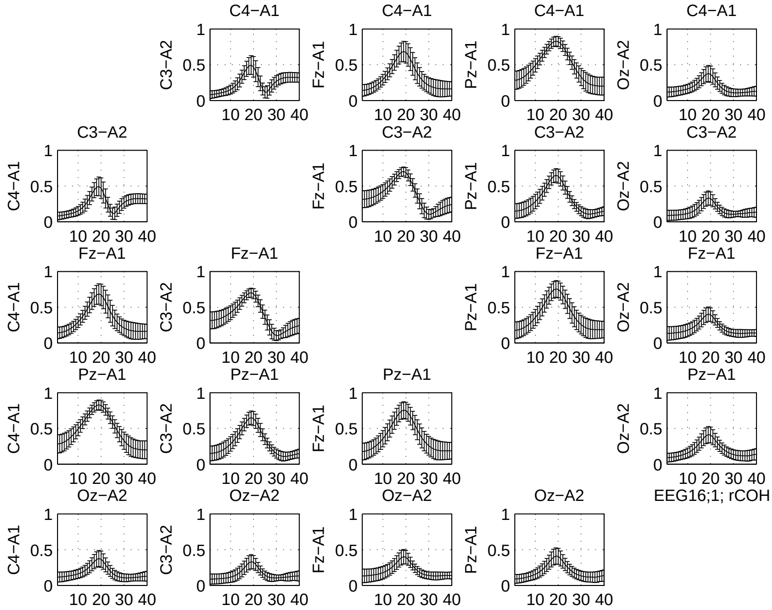

Figure 17: Magnitude coherence as in (5): Condition #1 & factor EEG16.*X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

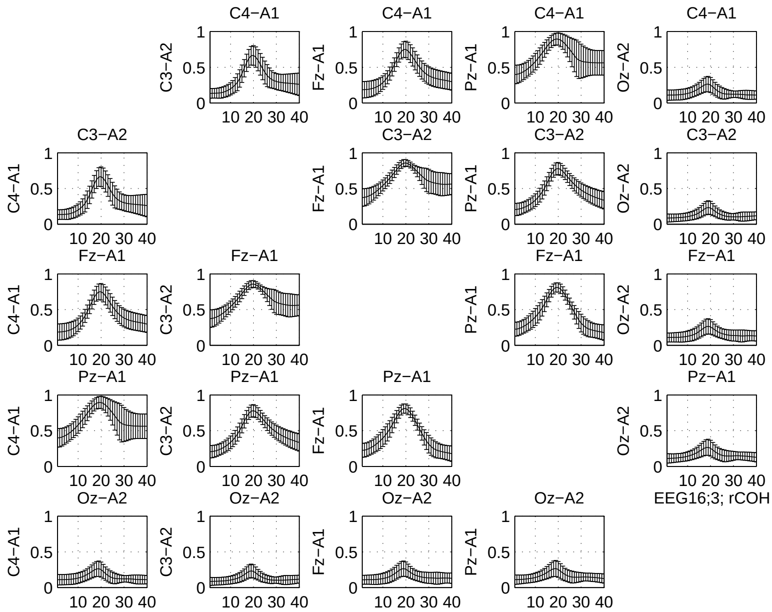

Figure 18: Magnitude coherence as in (5): Condition #3 & factor EEG16.*X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

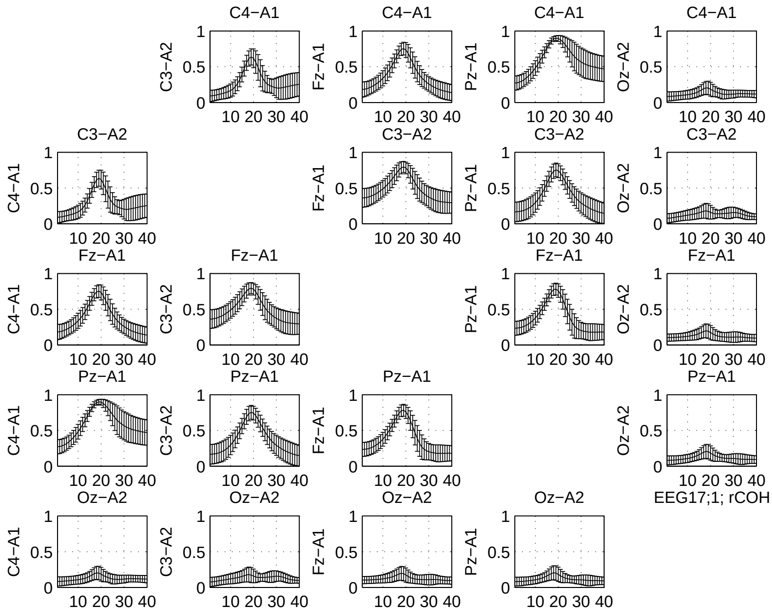

Figure 19: Magnitude coherence as in (5): Condition #1 & factor EEG17.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

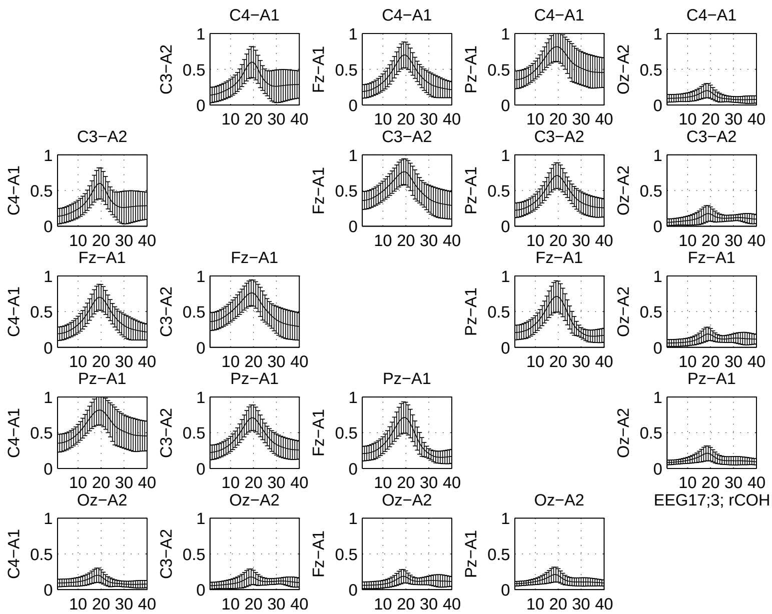

Figure 20: Magnitude coherence as in (5): Condition #3 & factor EEG17.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

3.2 Phase coherence

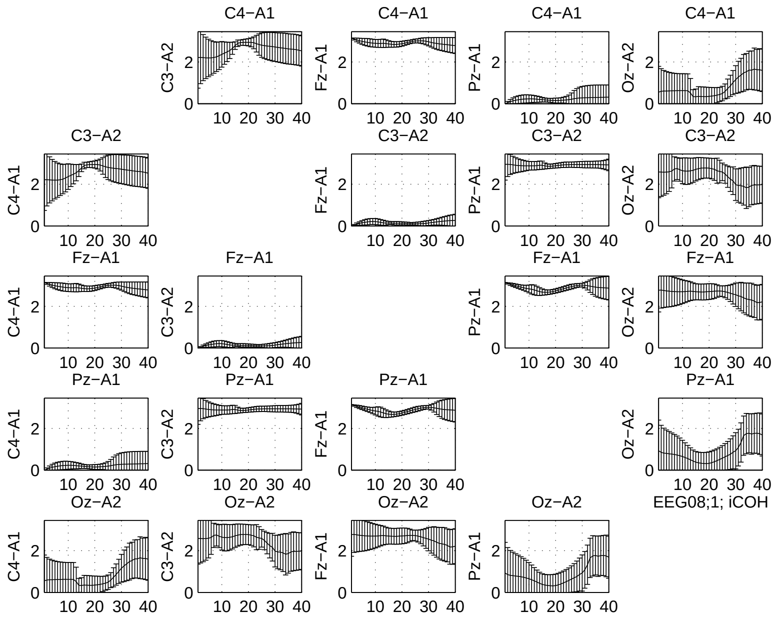

Figure 21: Phase coherence as in (6): Condition #1 & factor EEG08. *X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

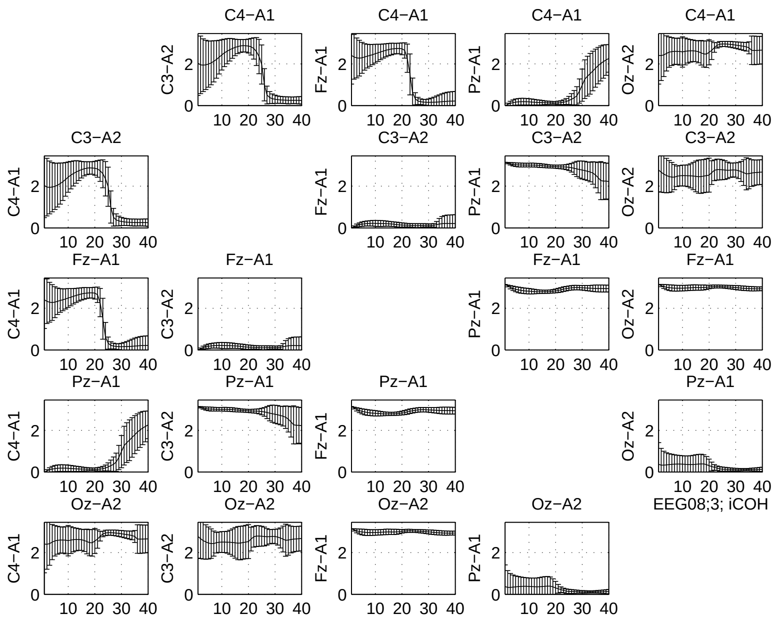

Figure 22: Phase coherence as in (6): Condition #3 & factor EEG08. *X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

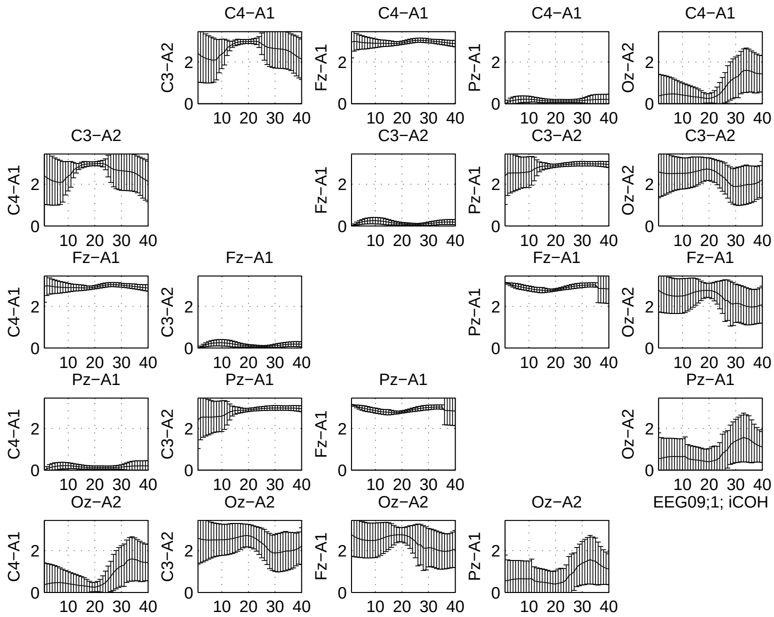

Figure 23: Phase coherence as in (6): Condition #1 & factor EEG09. *X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

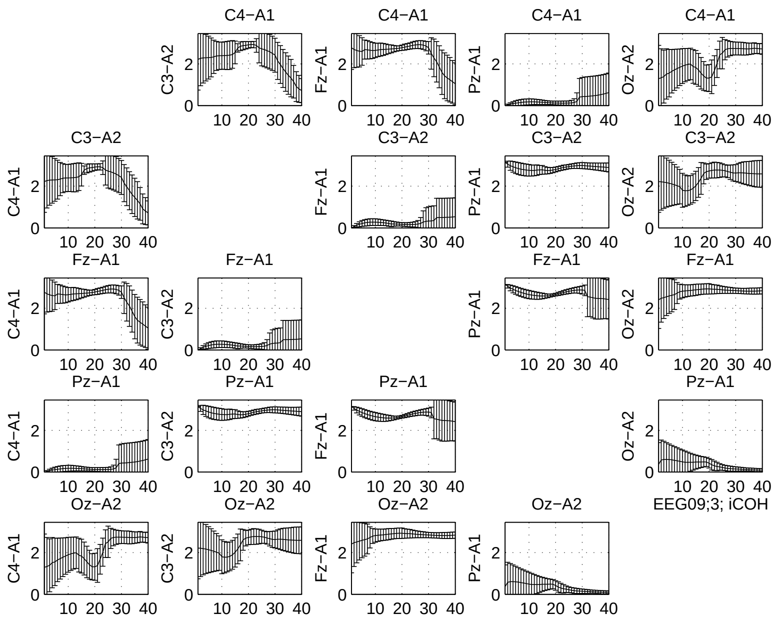

Figure 24: Phase coherence as in (6): Condition #3 & factor EEG09. *X-axes* in all plots are frequencies $0 - 20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

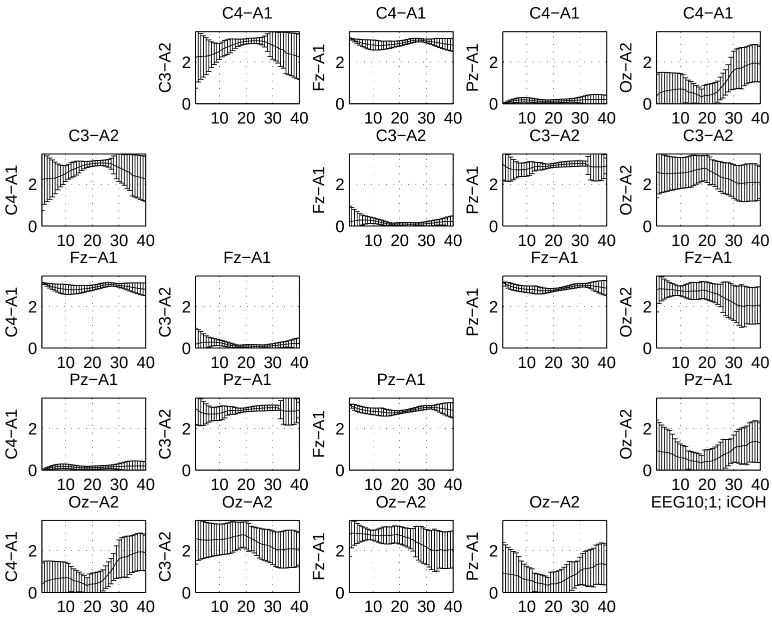

Figure 25: Phase coherence as in (6): Condition #1 & factor EEG10.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

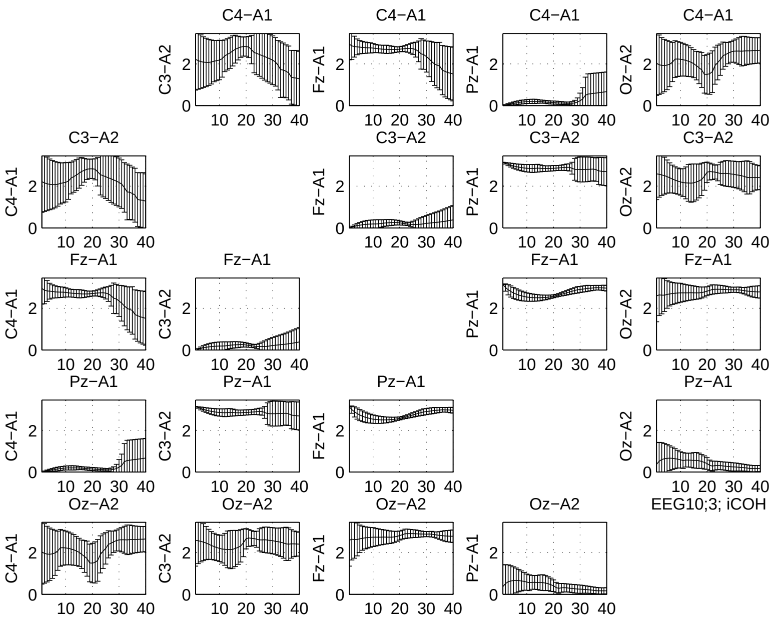

Figure 26: Phase coherence as in (6): Condition #3 & factor EEG10.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

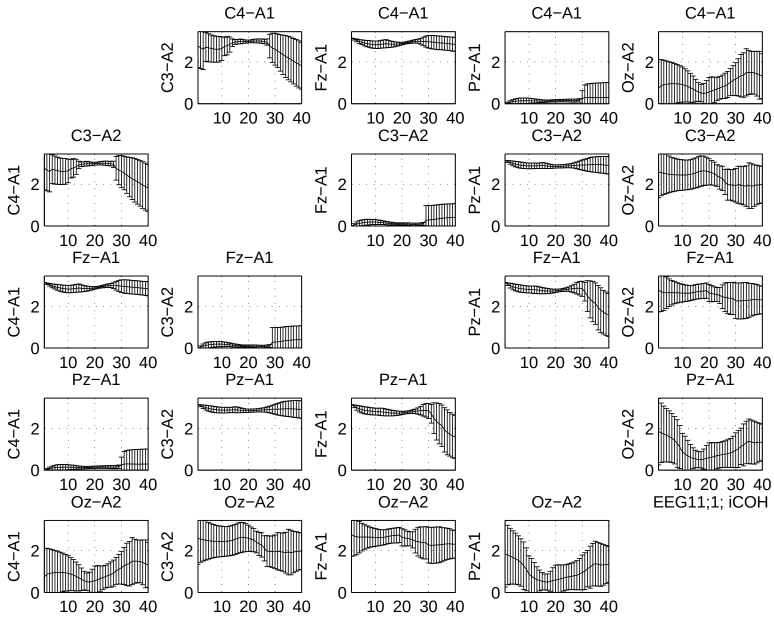

Figure 27: Phase coherence as in (6): Condition #1 & factor EEG11.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

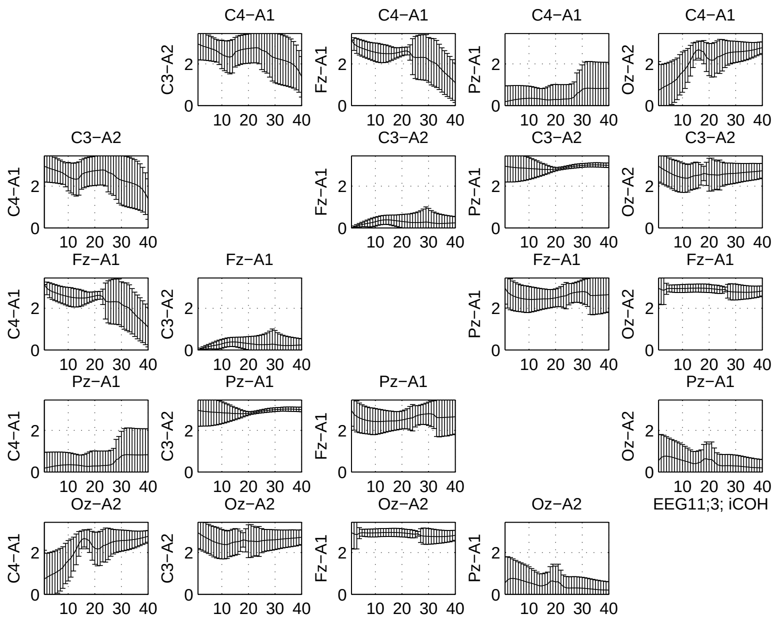

Figure 28: Phase coherence as in (6): Condition #3 & factor EEG11.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

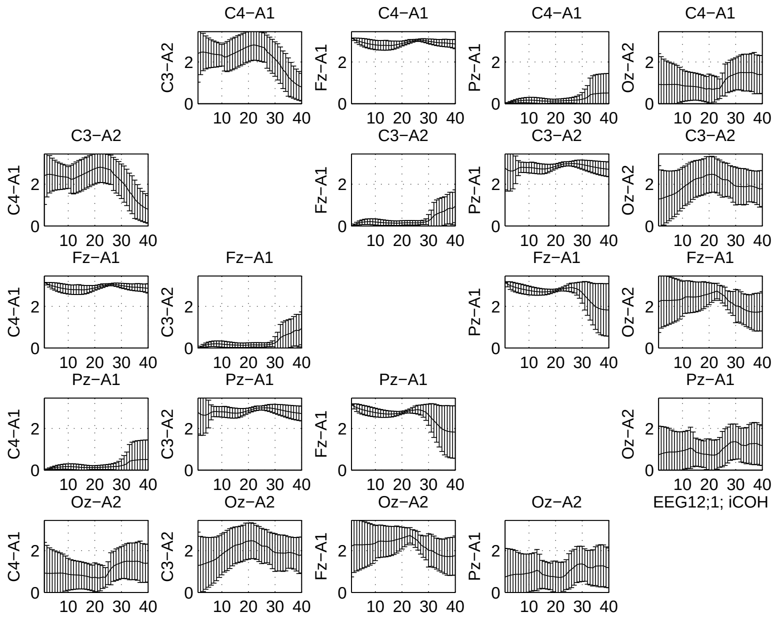

Figure 29: Phase coherence as in (6): Condition #1 & factor EEG12.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

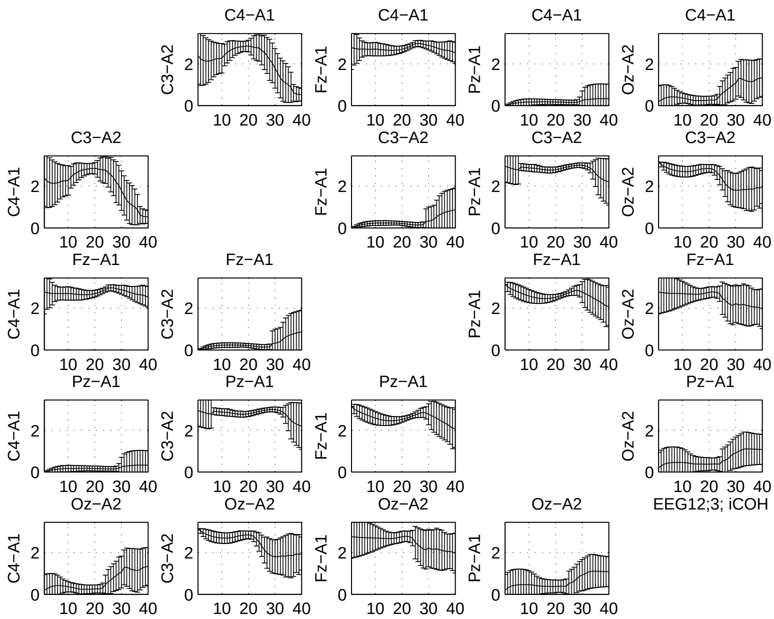

Figure 30: Phase coherence as in (6): Condition #3 & factor EEG12.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

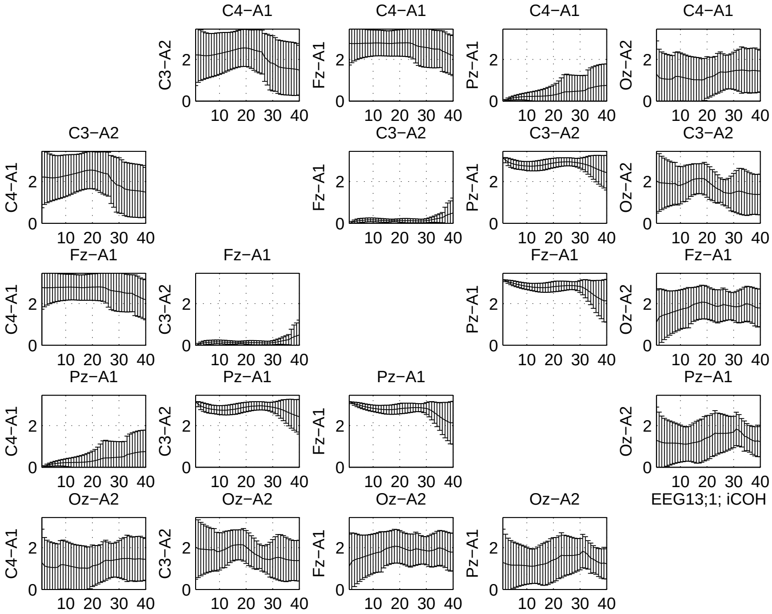

Figure 31: Phase coherence as in (6): Condition #1 & factor EEG13.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

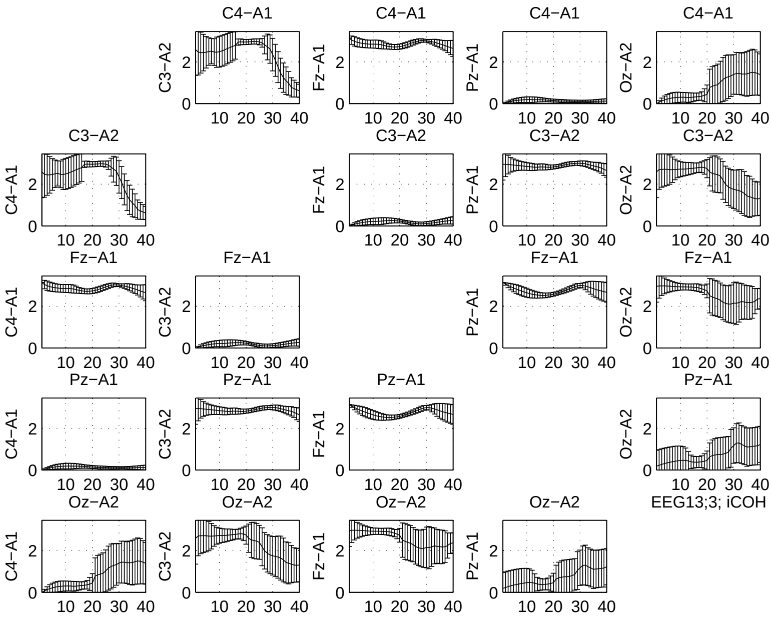

Figure 32: Phase coherence as in (6): Condition #3 & factor EEG13.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

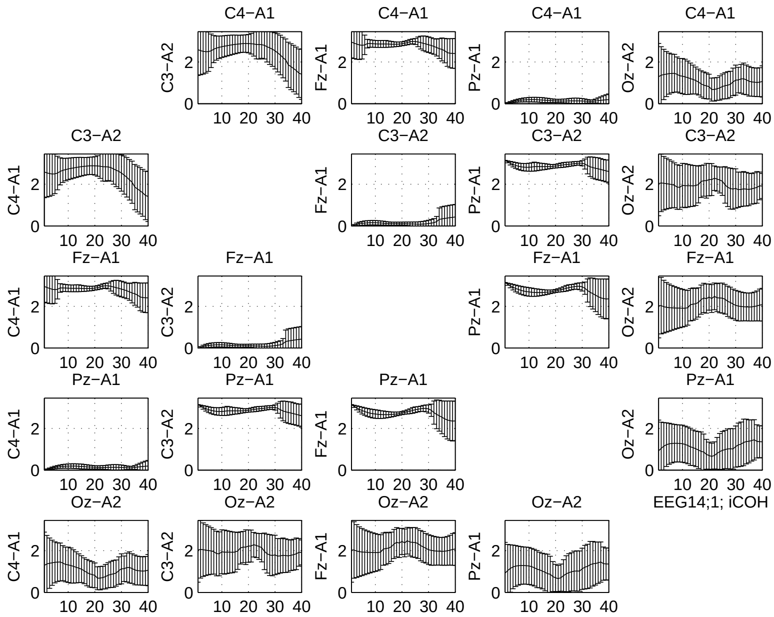

Figure 33: Phase coherence as in (6): Condition #1 & factor EEG14.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

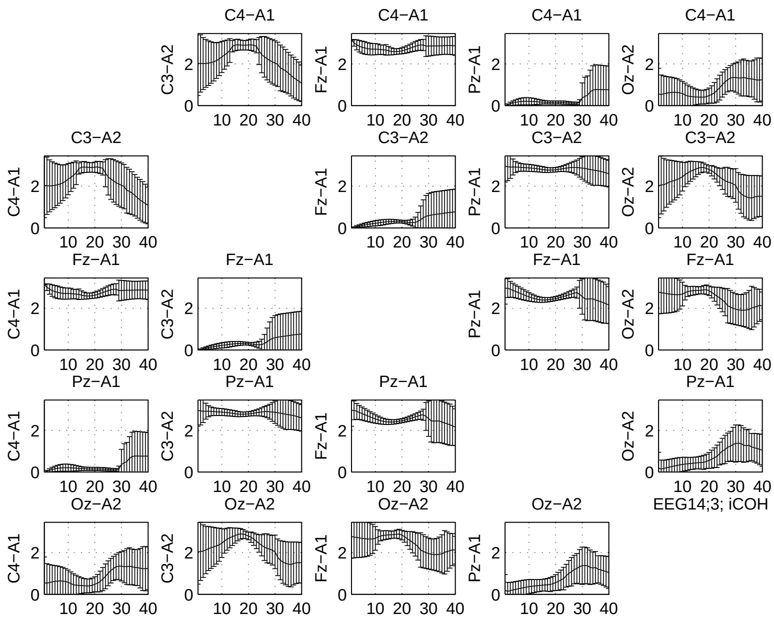

Figure 34: Phase coherence as in (6): Condition #3 & factor EEG14.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

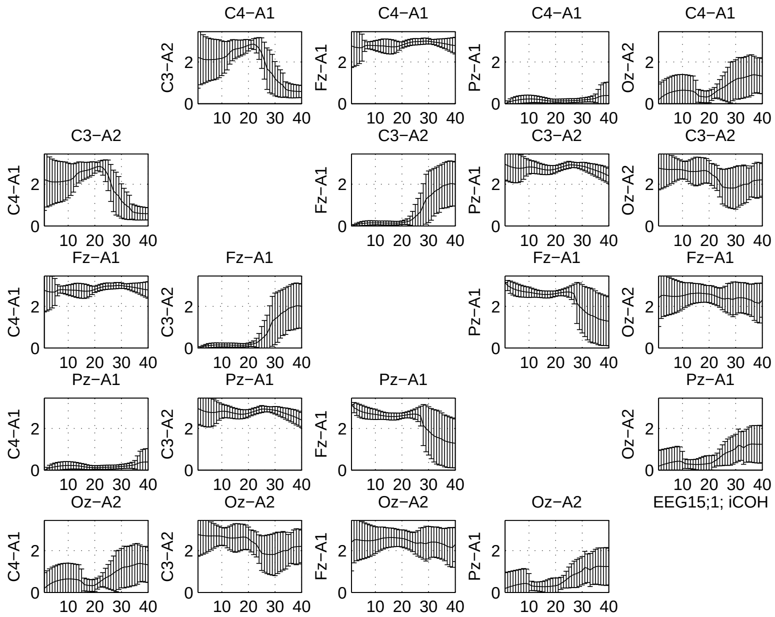

Figure 35: Phase coherence as in (6): Condition #1 & factor EEG15.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

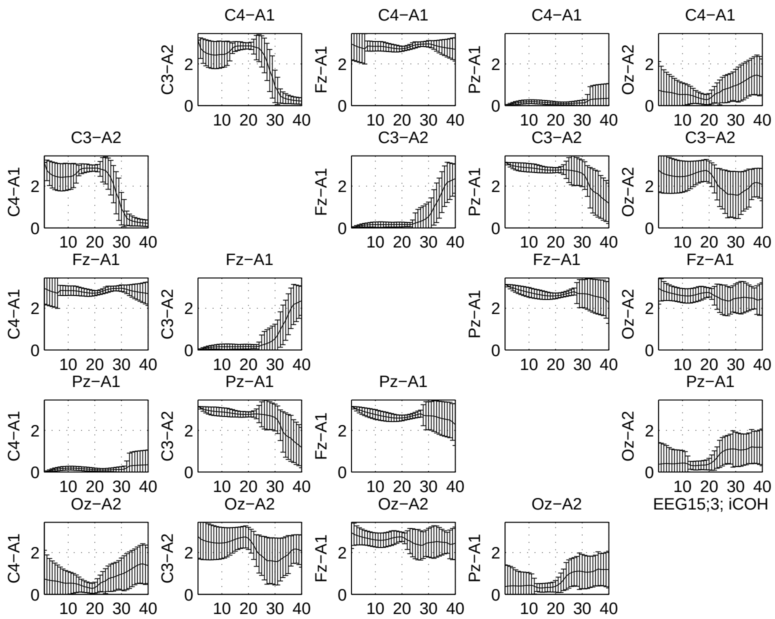

Figure 36: Phase coherence as in (6): Condition #3 & factor EEG15.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

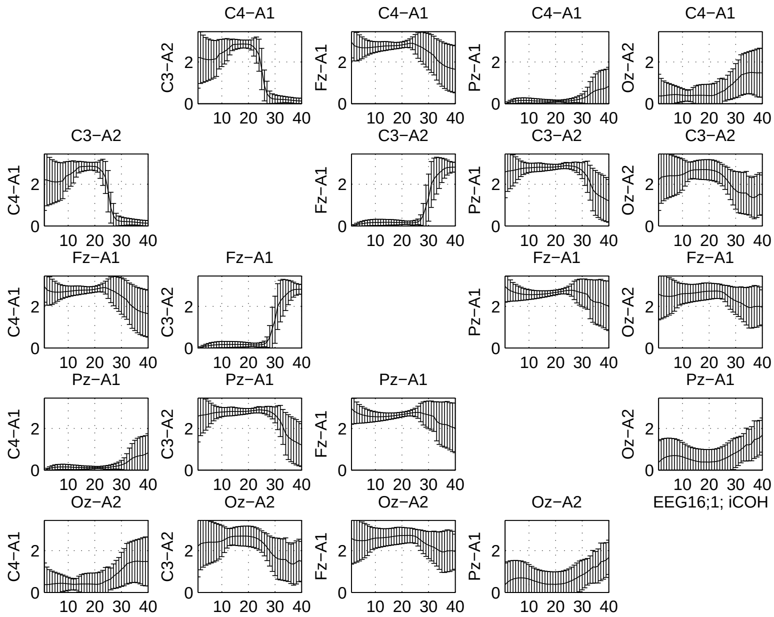

Figure 37: Phase coherence as in (6): Condition #1 & factor EEG16.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

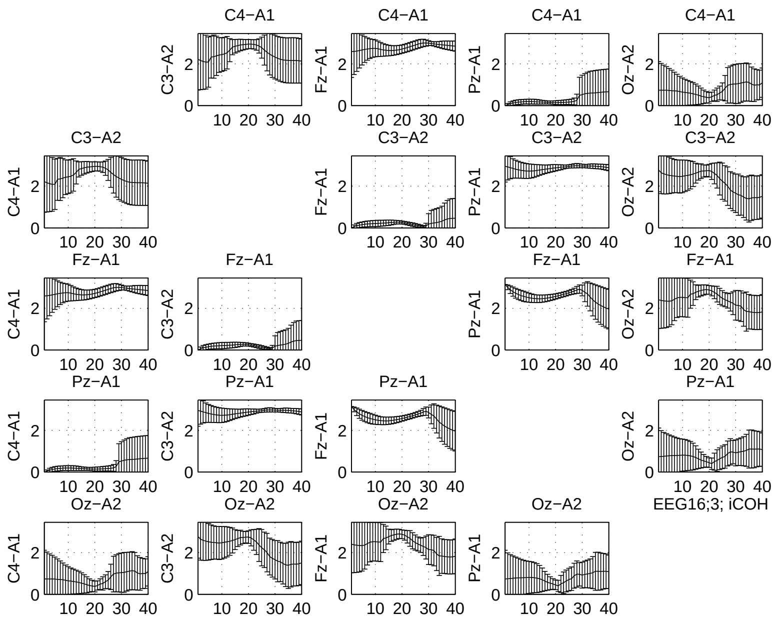

Figure 38: Phase coherence as in (6): Condition #3 & factor EEG16.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

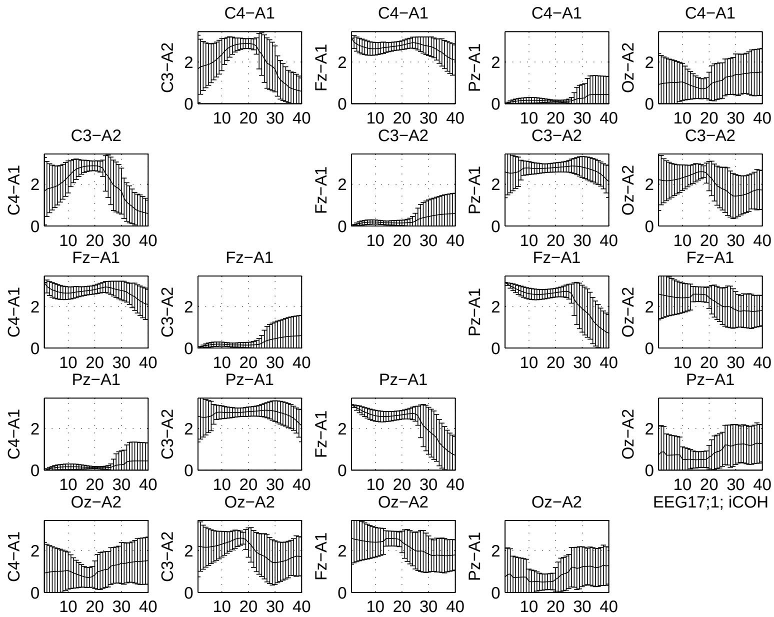

Figure 39: Phase coherence as in (6): Condition #1 & factor EEG17.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

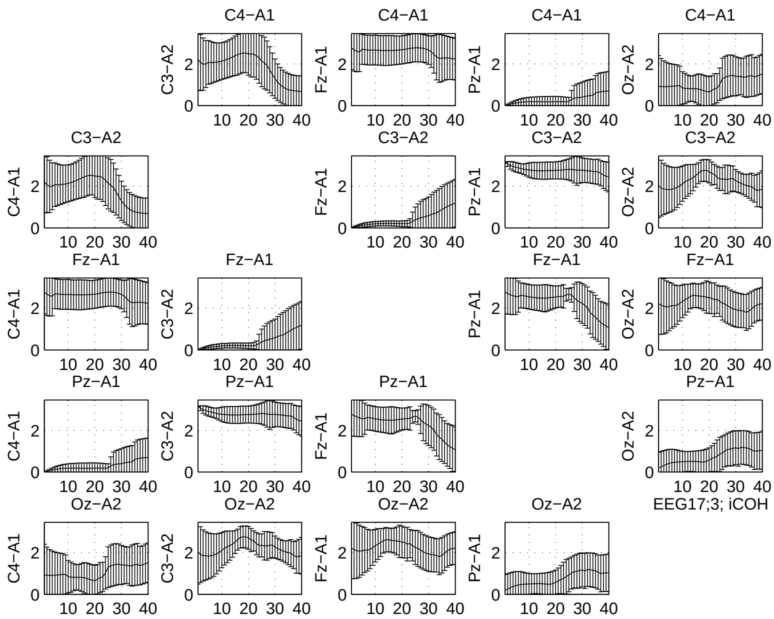

Figure 40: Phase coherence as in (6): Condition #3 & factor EEG17.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

3.3 Directed transfer function (DTF)

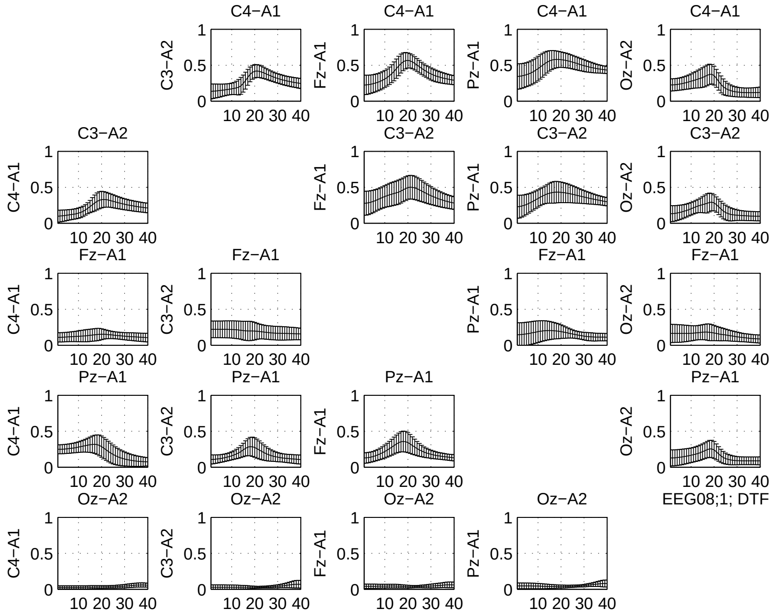

Figure 41: DTF as in (9): Condition #1 and factor EEG08. *X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

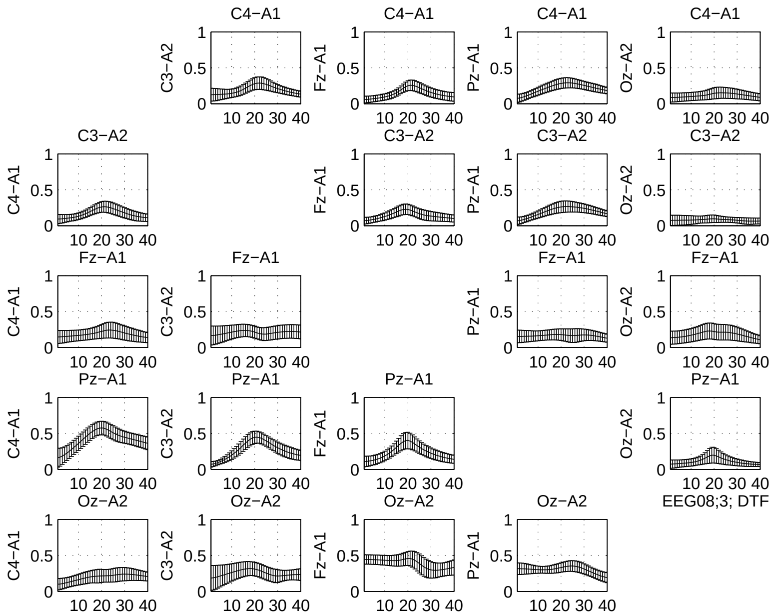

Figure 42: DTF as in (9): Condition #3 and EEG08. *X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

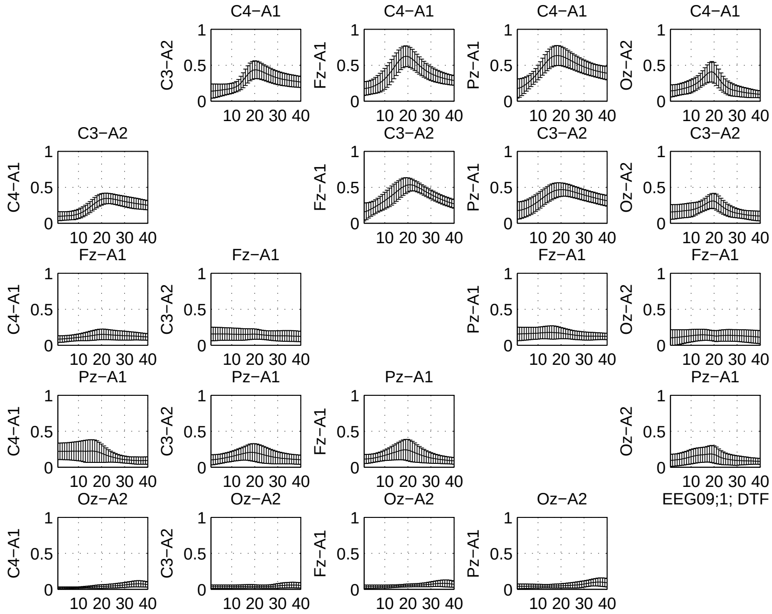

Figure 43: DTF as in (9): Condition #1 and factor EEG09.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

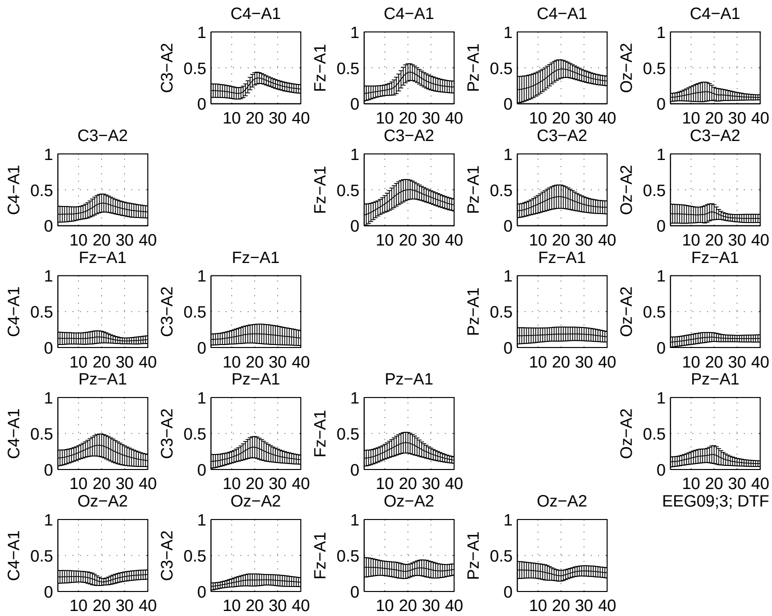

Figure 44: DTF as in (9): Condition #3 and EEG09.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

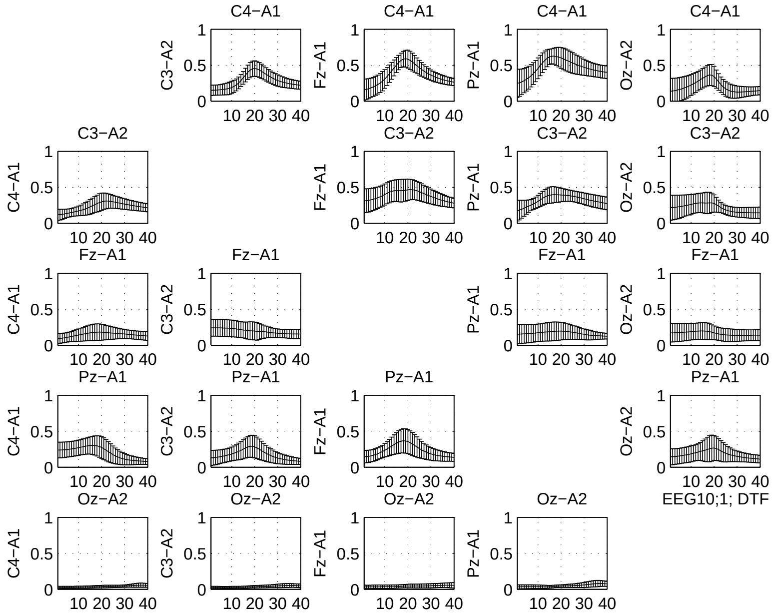

Figure 45: DTF as in (9): Condition #1 and factor EEG10.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

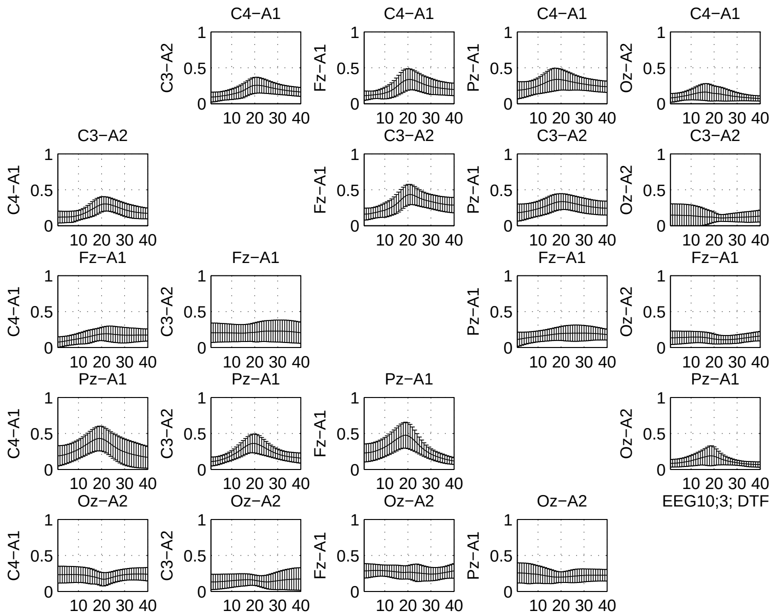

Figure 46: DTF as in (9): Condition #3 and EEG10.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

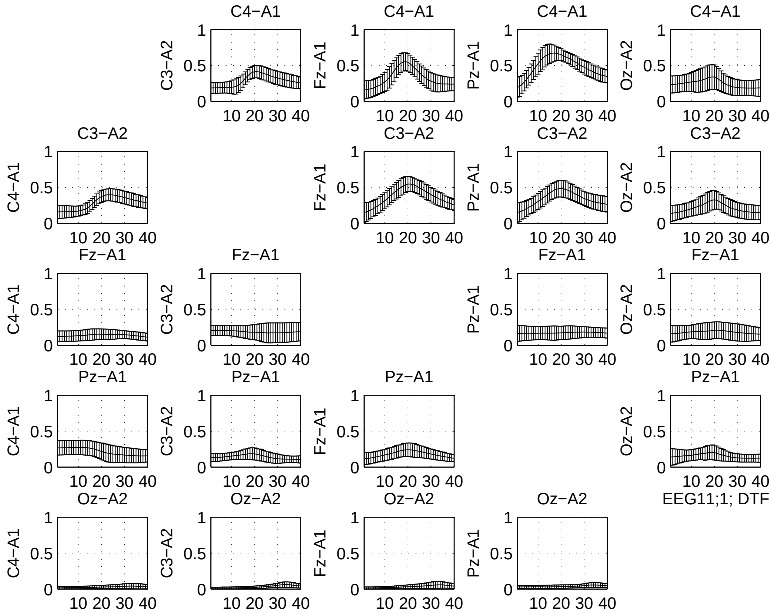

Figure 47: DTF as in (9): Condition #1 and factor EEG11.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

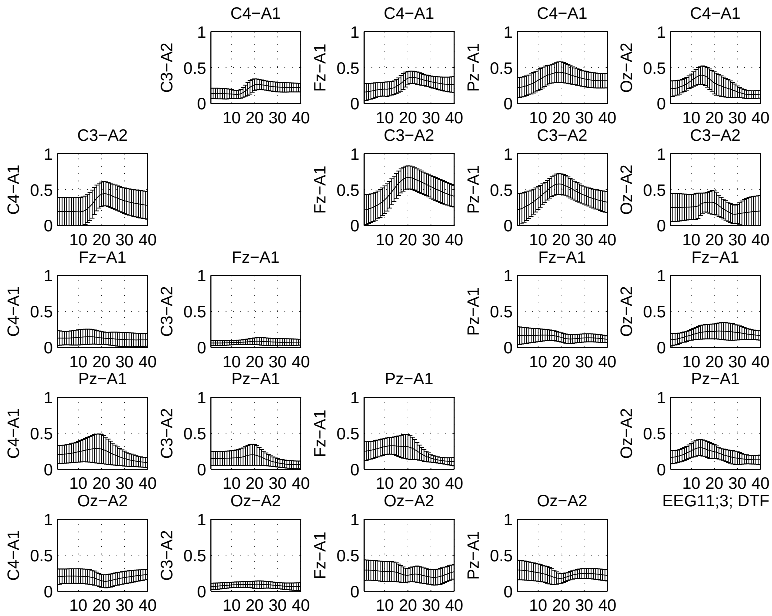

Figure 48: DTF as in (9): Condition #3 and EEG11.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

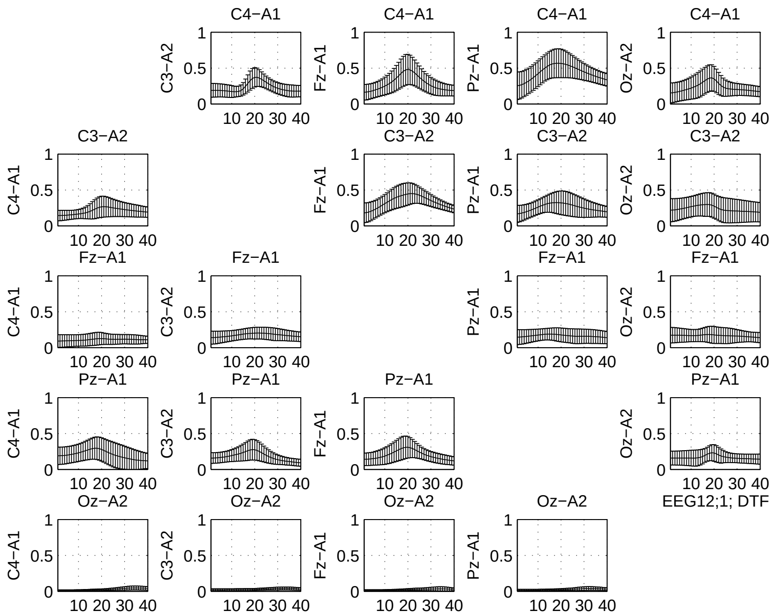

Figure 49: DTF as in (9): Condition #1 and factor EEG12.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

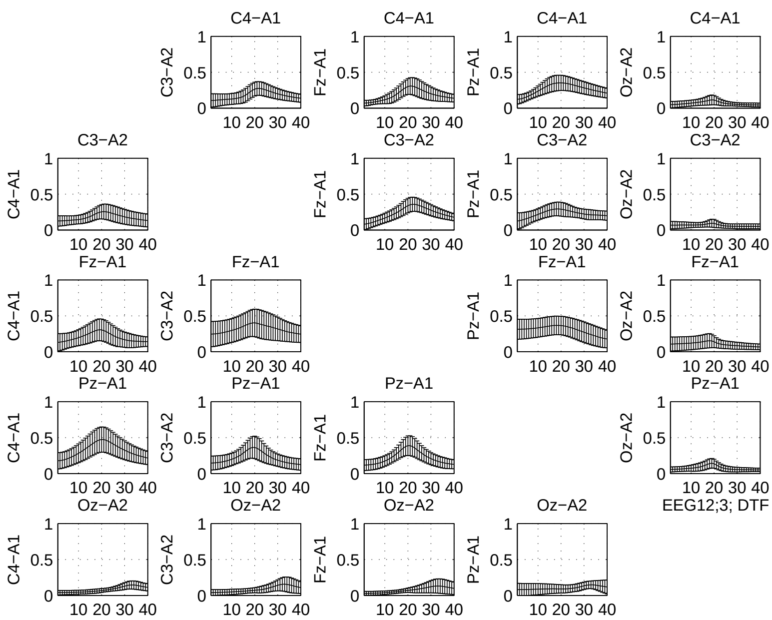

Figure 50: DTF as in (9): Condition #3 and EEG12.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

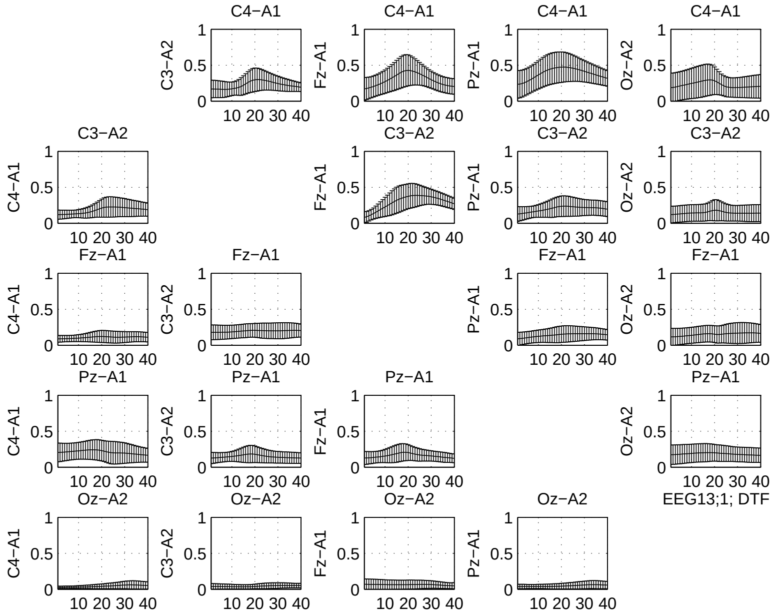

Figure 51: DTF as in (9): Condition #1 and factor EEG13.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

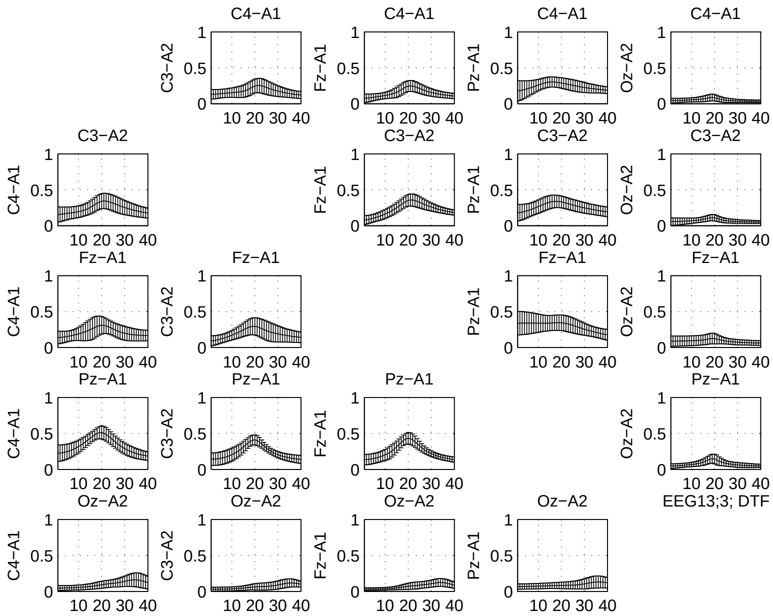

Figure 52: DTF as in (9): Condition #3 and EEG13.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

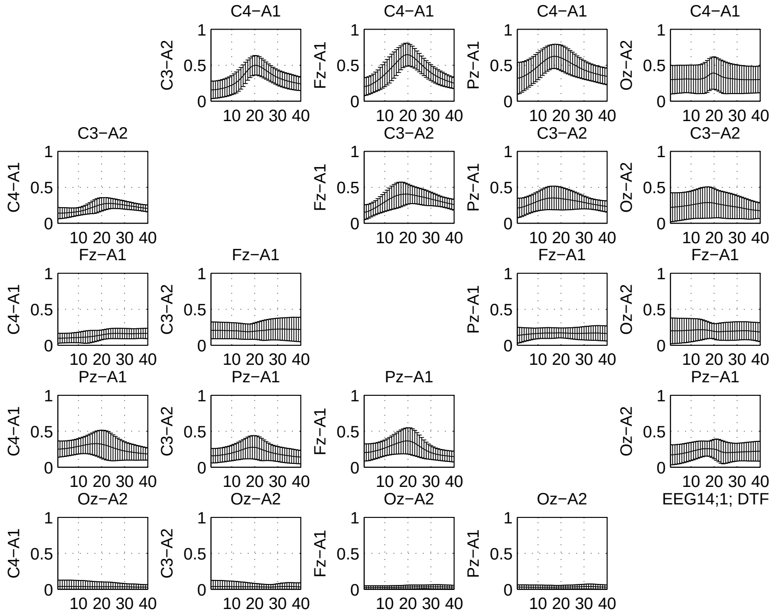

Figure 53: DTF as in (9): Condition #1 and factor EEG14.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

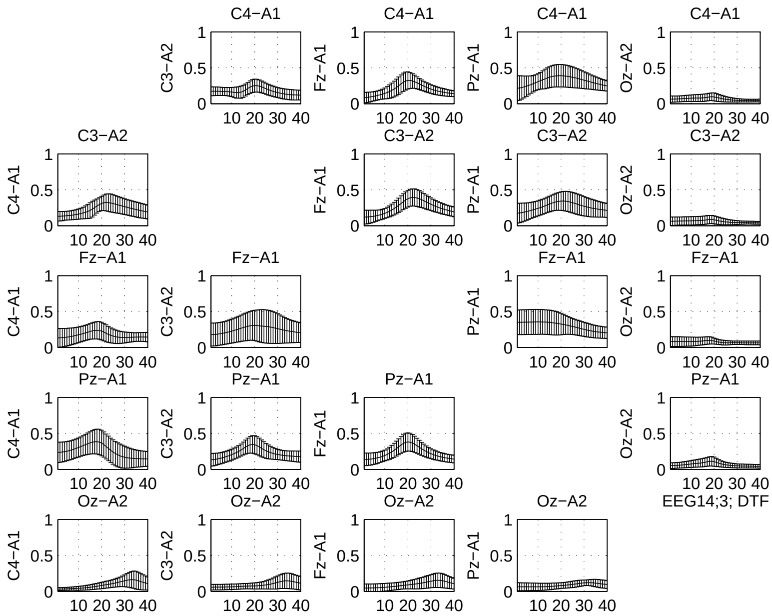

Figure 54: DTF as in (9): Condition #3 and EEG14.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

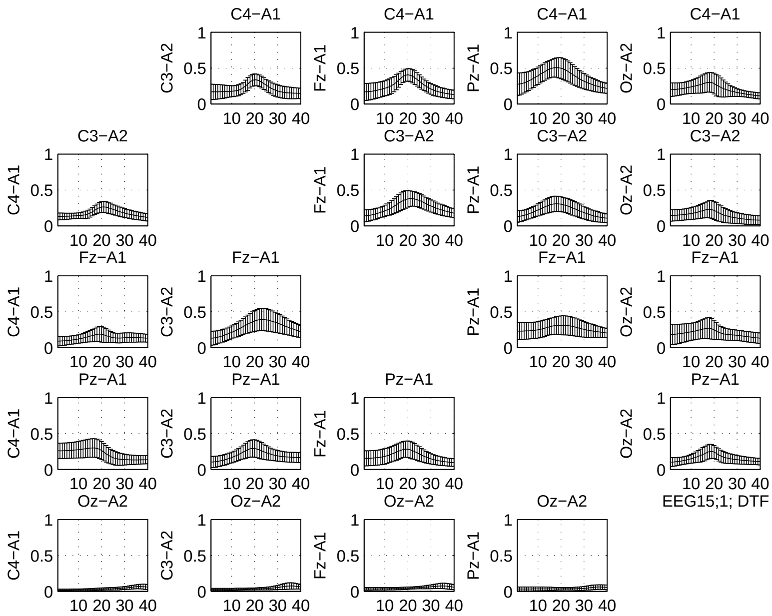

Figure 55: DTF as in (9): Condition #1 and factor EEG15.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

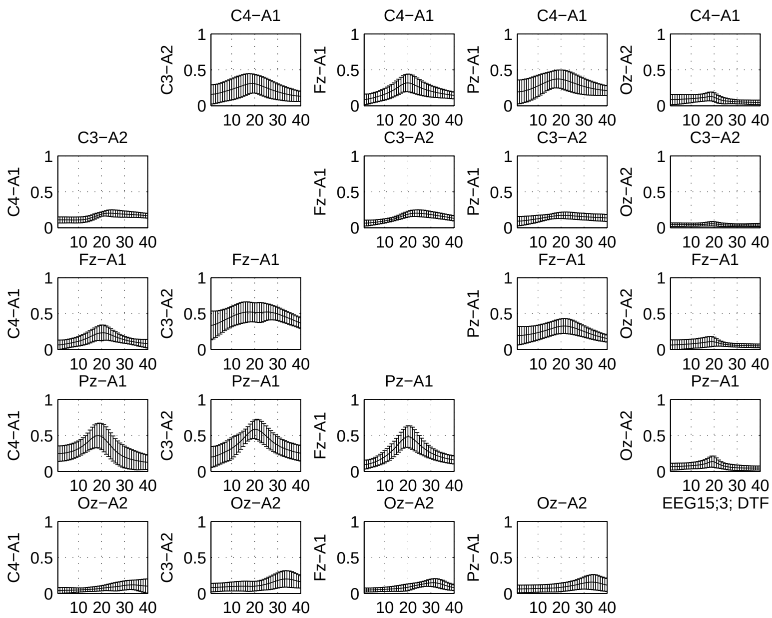

Figure 56: DTF as in (9): Condition #3 and EEG15.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

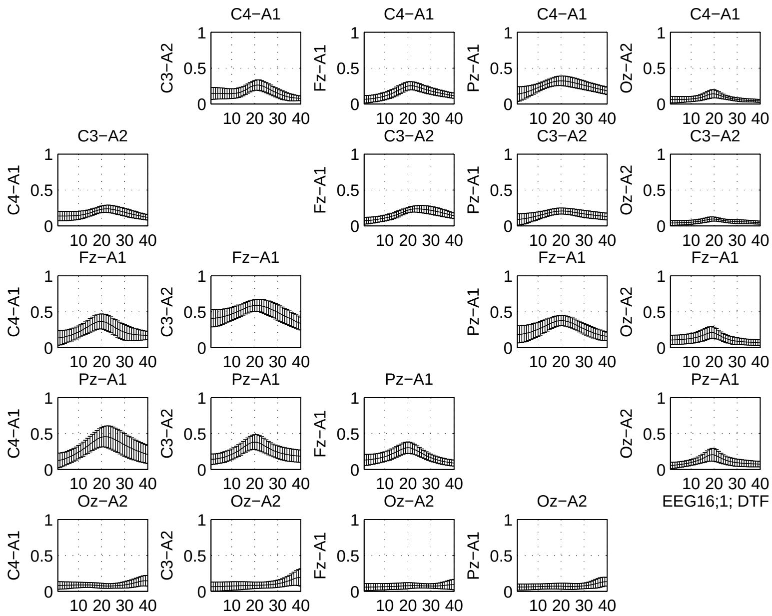

Figure 57: DTF as in (9): Condition #1 and factor EEG16.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

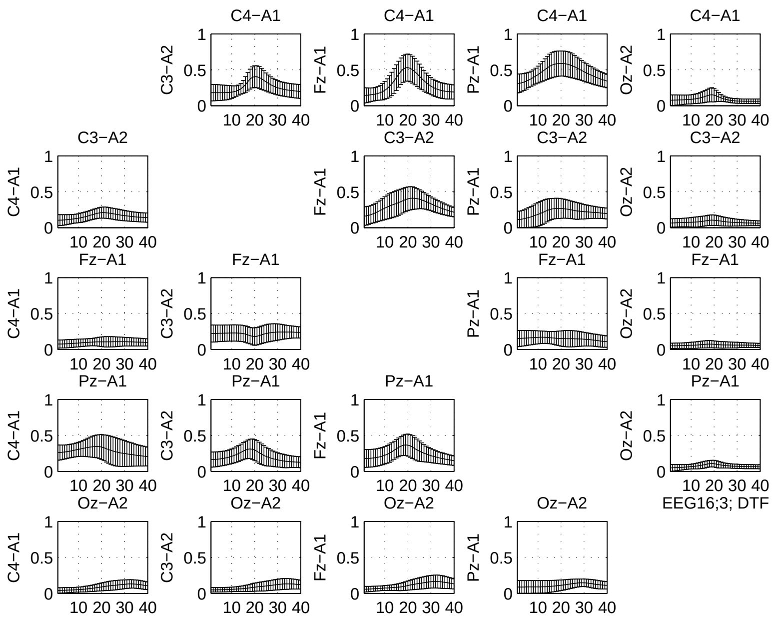

Figure 58: DTF as in (9): Condition #3 and EEG16.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

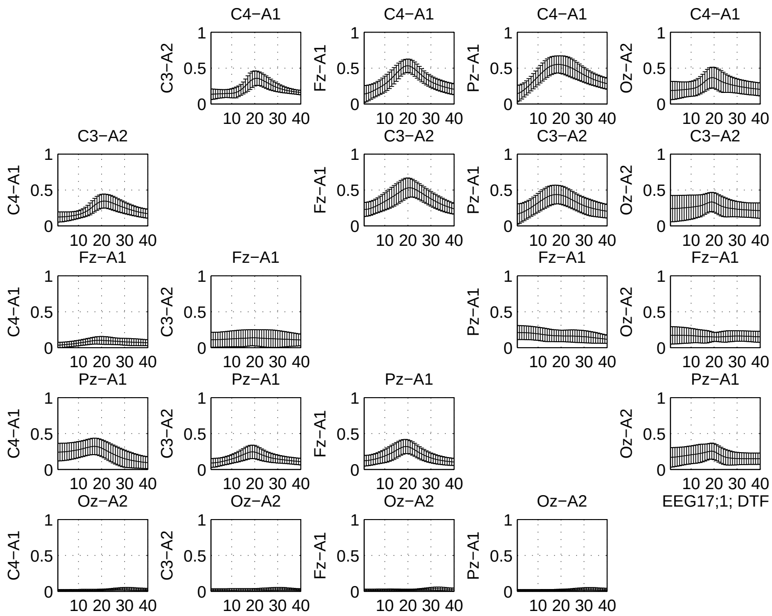

Figure 59: DTF as in (9): Condition #1 and factor EEG17.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

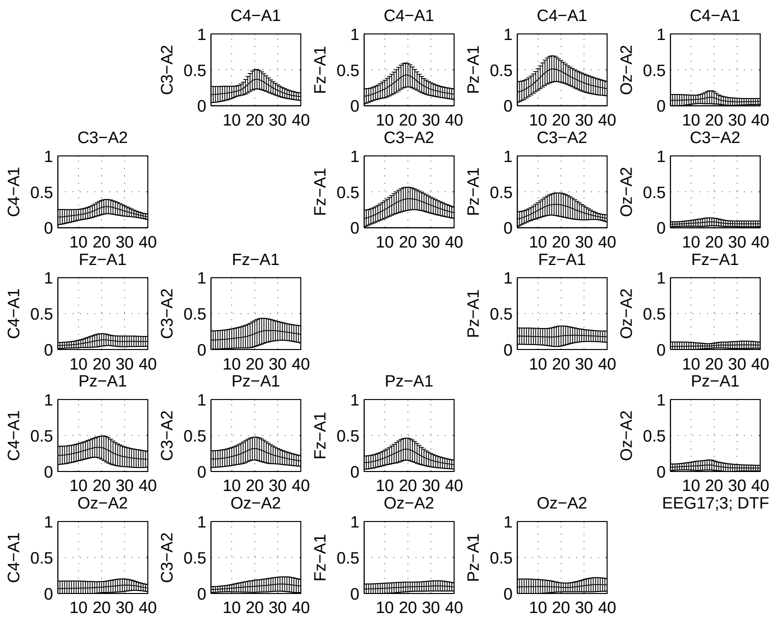

Figure 60: DTF as in (9): Condition #3 and EEG17.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

3.4 Direct directed transfer function (dDTF)

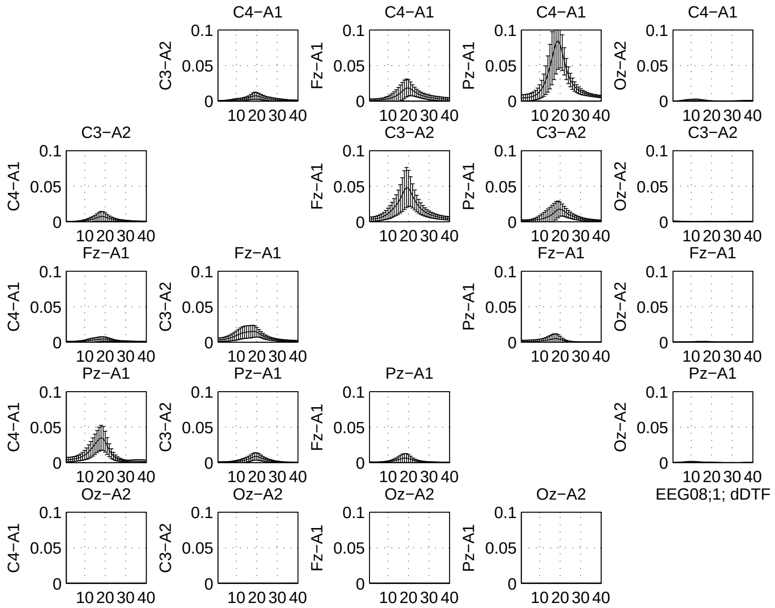

Figure 61: dDTF as in (11): as in (9): Condition #1 and EEG08. *X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

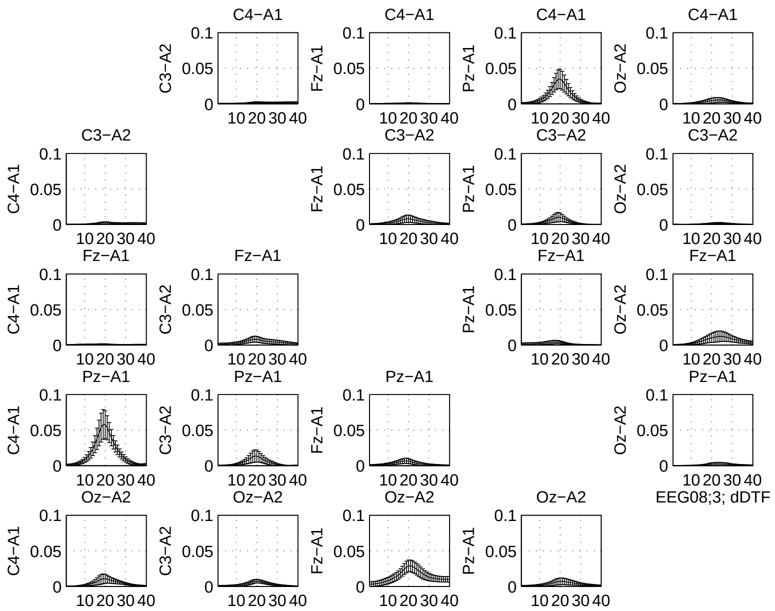

Figure 62: dDTF as in (11): Condition #3 and EEG08. *X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

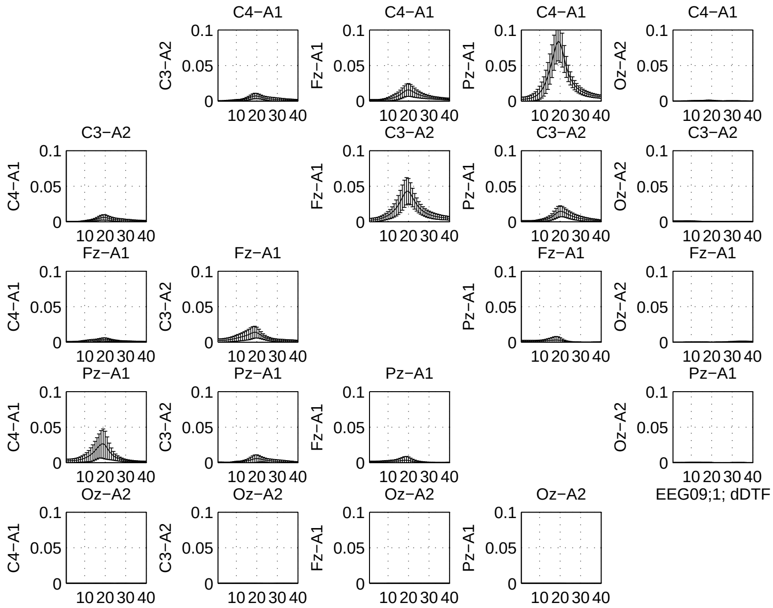

Figure 63: dDTF as in (11): Condition #1 and EEG09.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

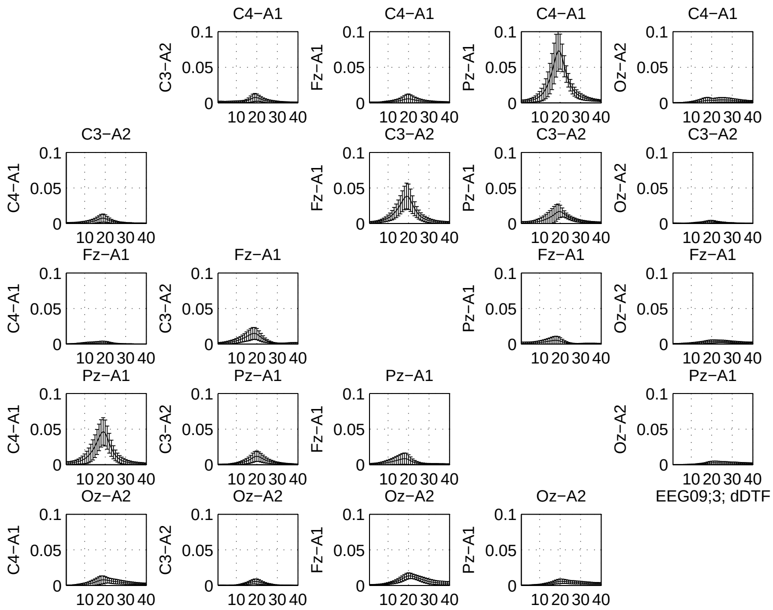

Figure 64: dDTF as in (11): Condition #3 and EEG09.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

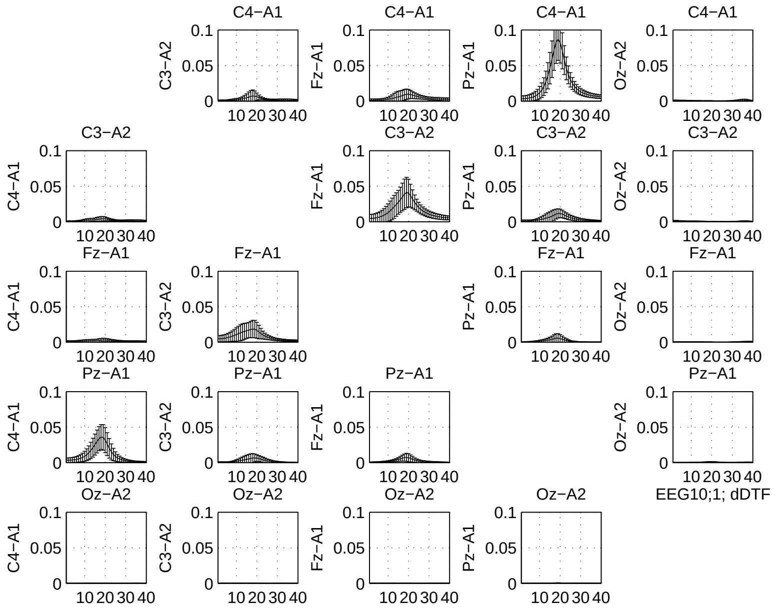

Figure 65: dDTF as in (11): Condition #1 and EEG10.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

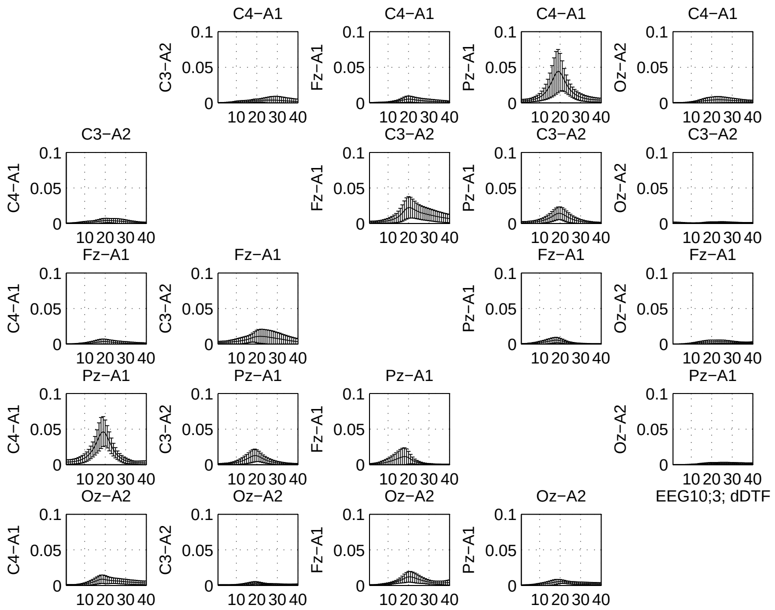

Figure 66: dDTF as in (11): Condition #3 and EEG10.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

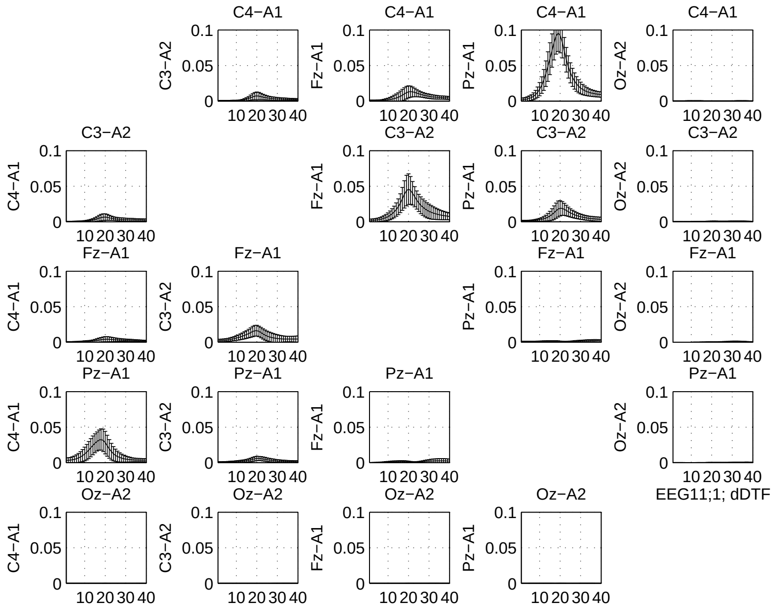

Figure 67: dDTF as in (11): Condition #1 and EEG11.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

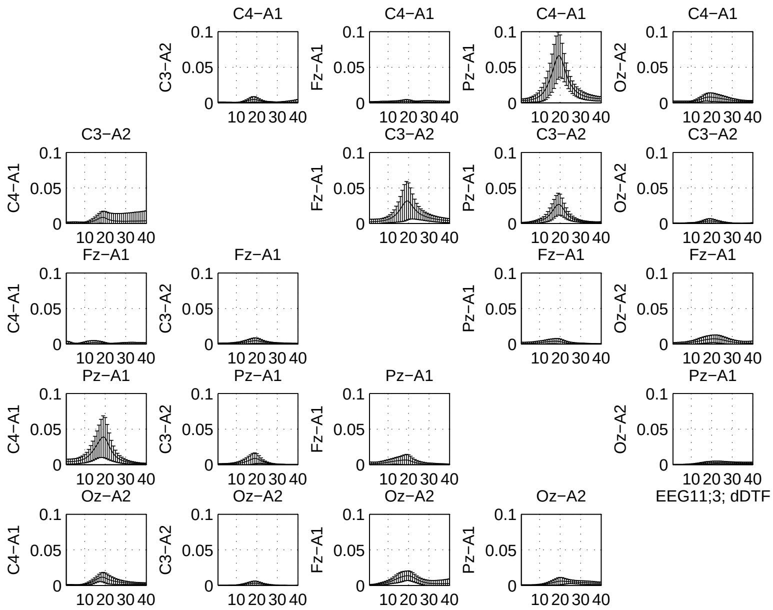

Figure 68: dDTF as in (11): Condition #3 and EEG11.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

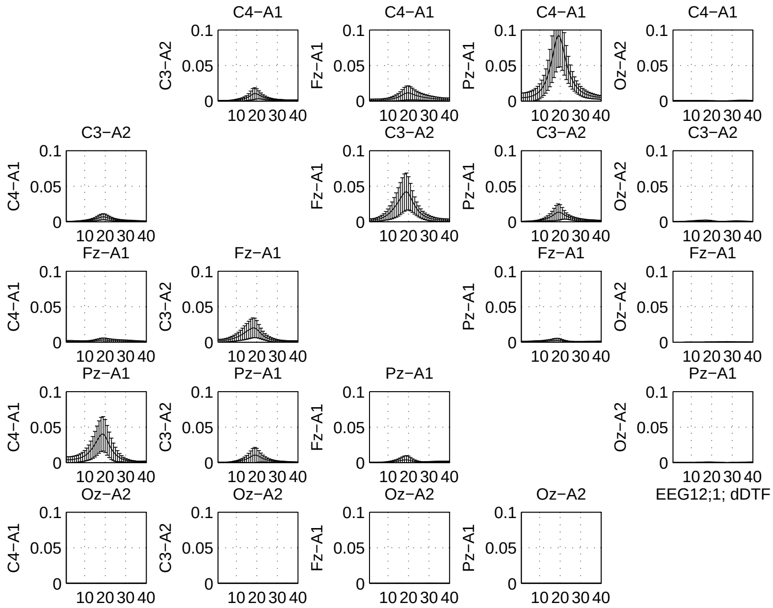

Figure 69: dDTF as in (11): Condition #1 and EEG12.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

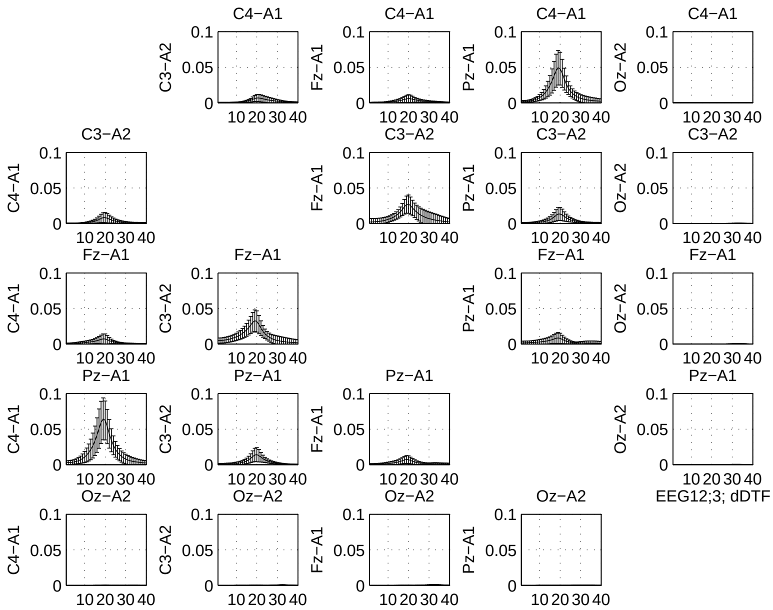

Figure 70: dDTF as in (11): Condition #3 and EEG12.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

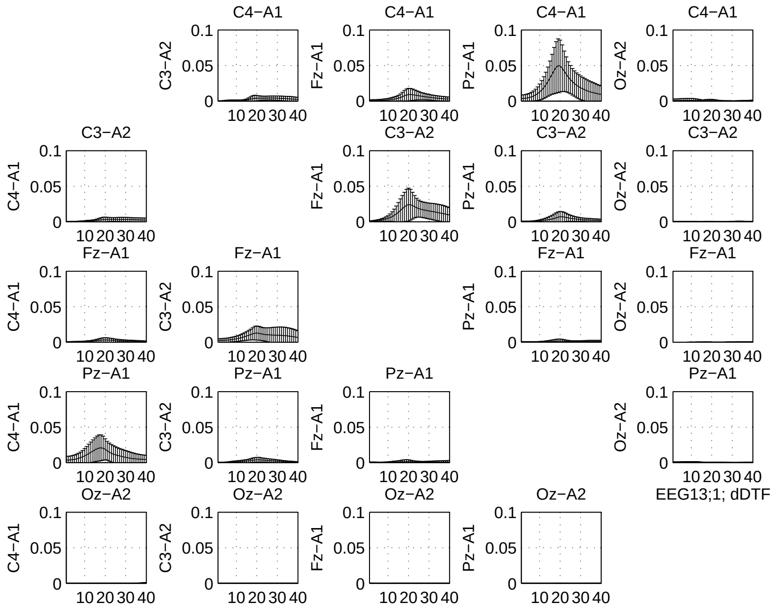

Figure 71: dDTF as in (11): Condition #1 and EEG13.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

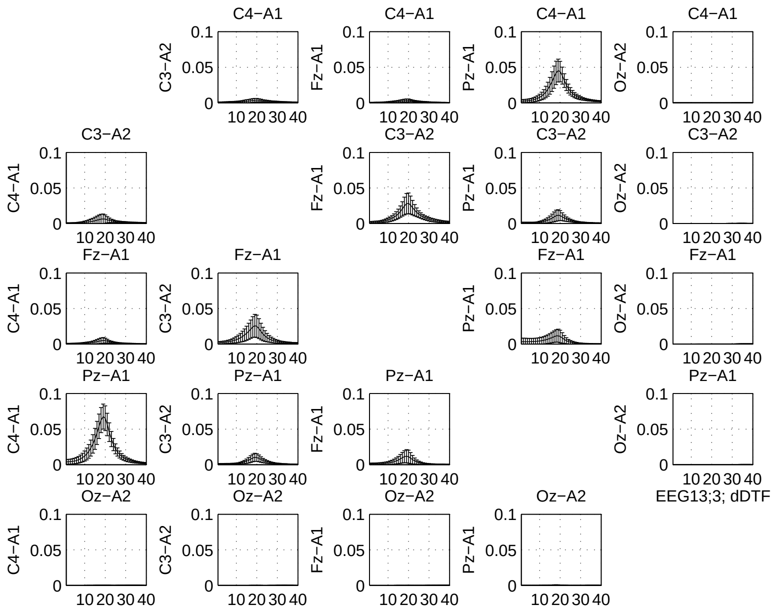

Figure 72: dDTF as in (11): Condition #3 and EEG13.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

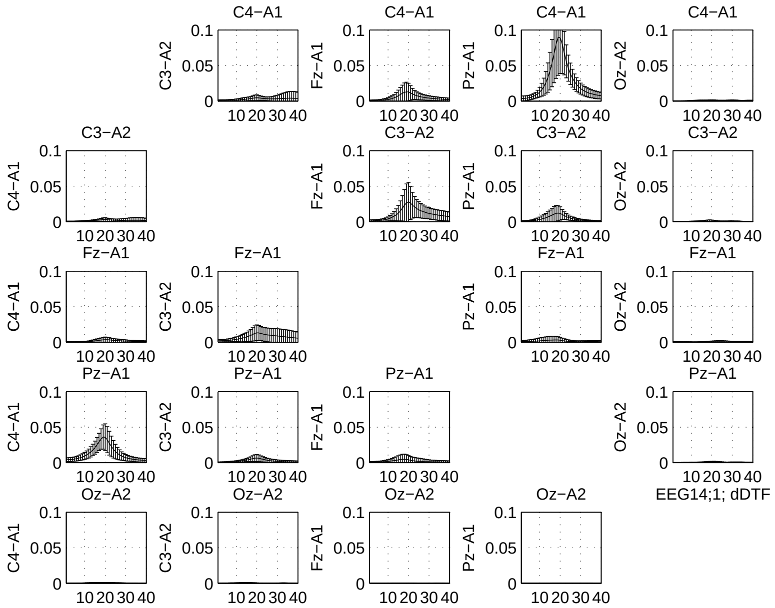

Figure 73: dDTF as in (11): Condition #1 and EEG14.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

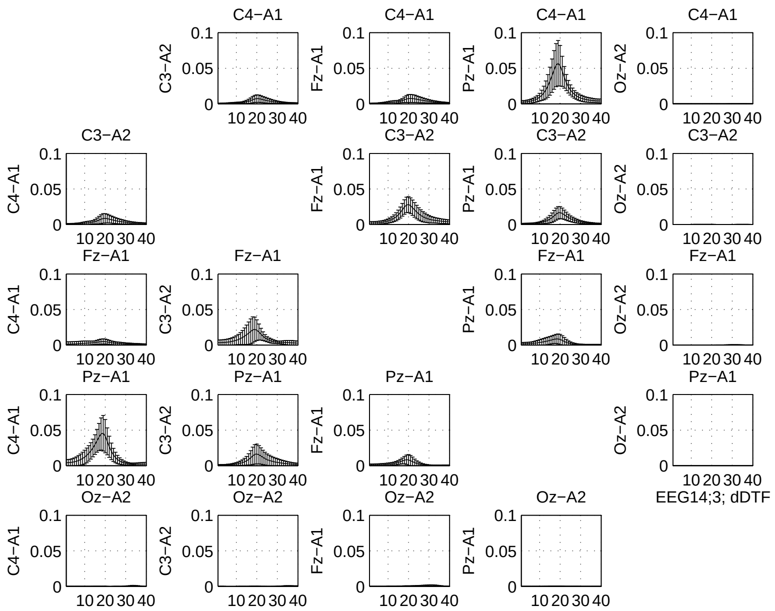

Figure 74: dDTF as in (11): Condition #3 and EEG14.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

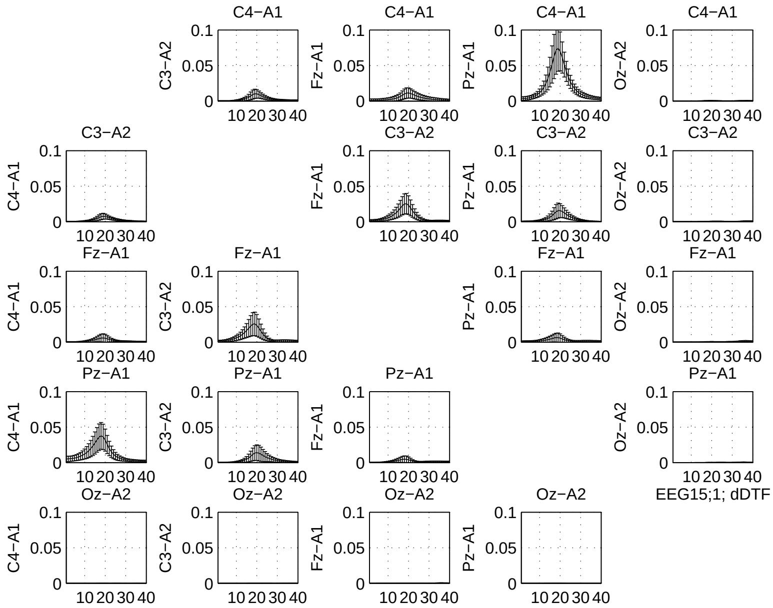

Figure 75: dDTF as in (11): Condition #1 and EEG15.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

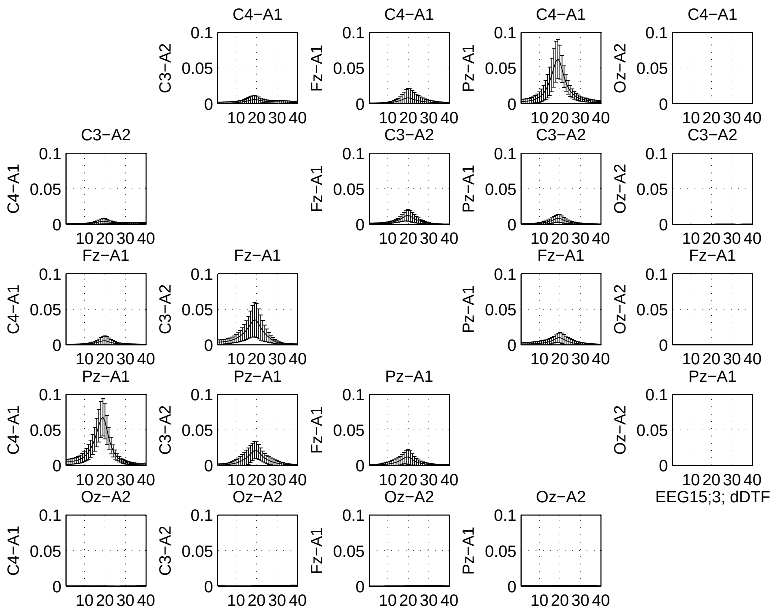

Figure 76: dDTF as in (11): Condition #3 and EEG15.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

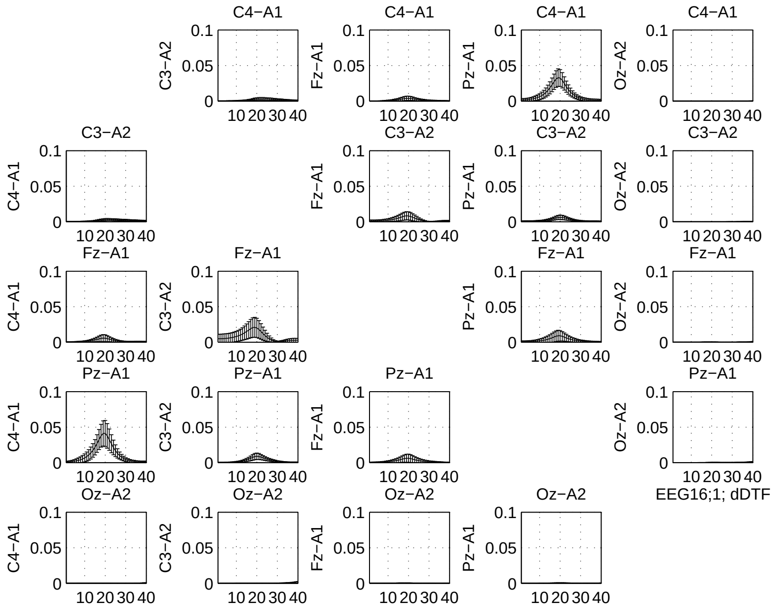

Figure 77: dDTF as in (11): Condition #1 and EEG16.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

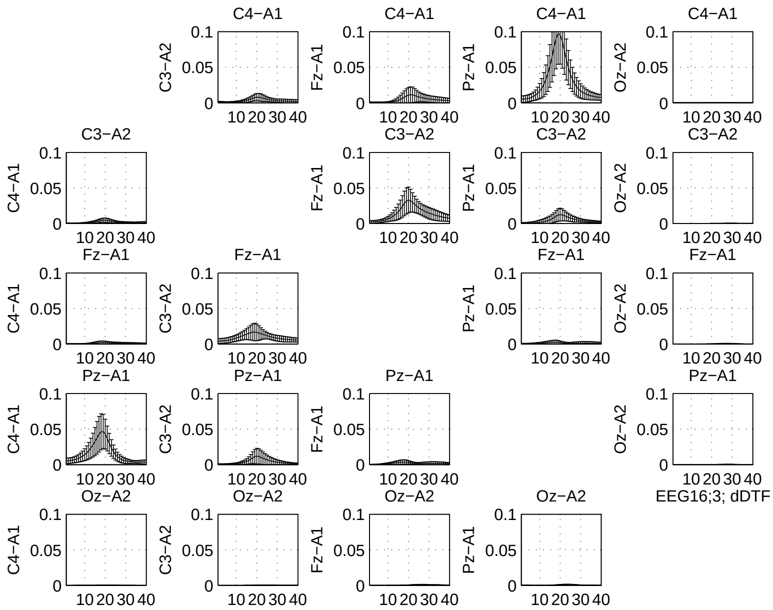

Figure 78: dDTF as in (11): Condition #3 and EEG16.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

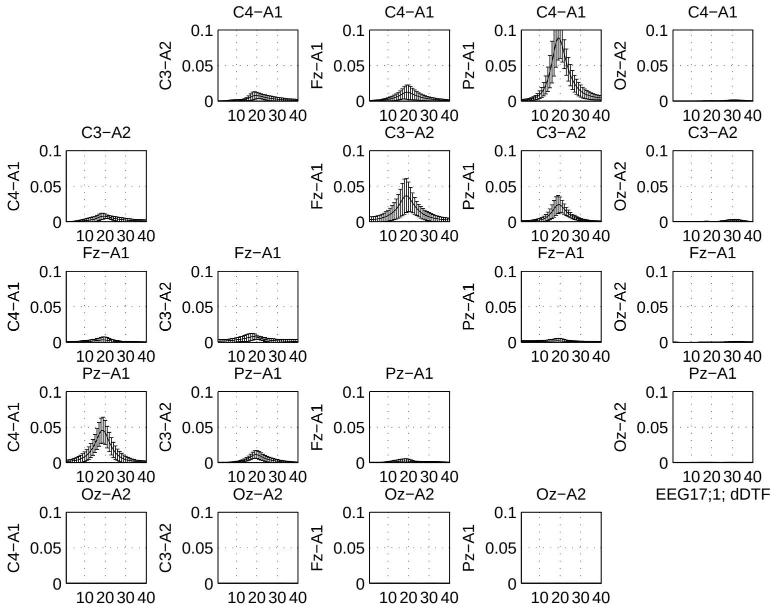

Figure 79: dDTF as in (11): Condition #1 and EEG17.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

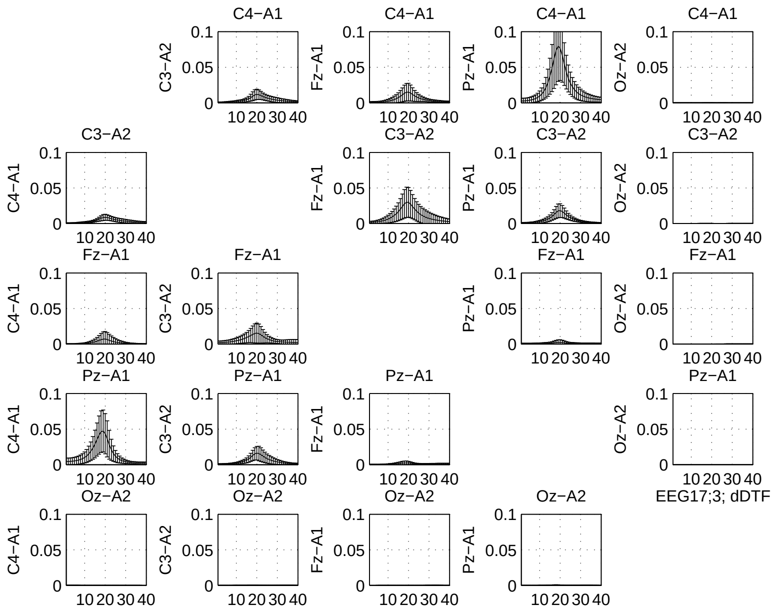

Figure 80: dDTF as in (11): Condition #3 and EEG17.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

3.5 Partial directed coherence (PDC)

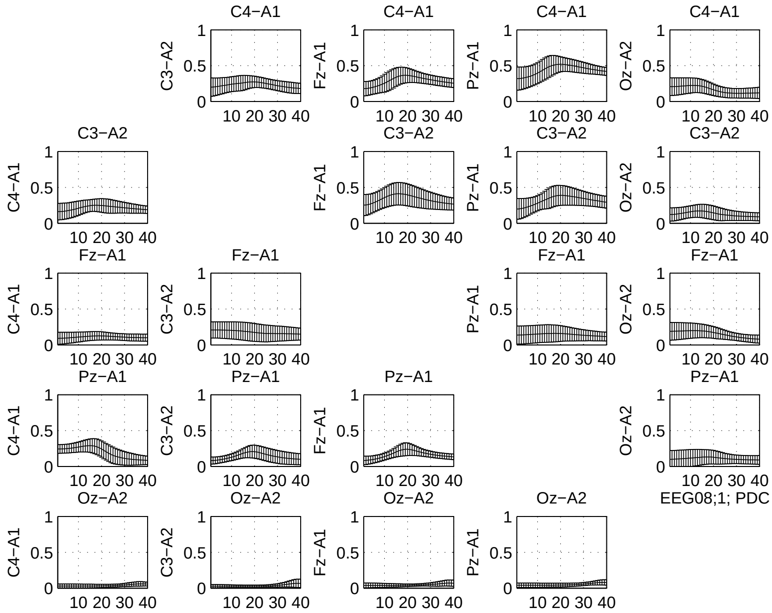

Figure 81: PDC as in (10): Condition #1 and EEG08. *X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

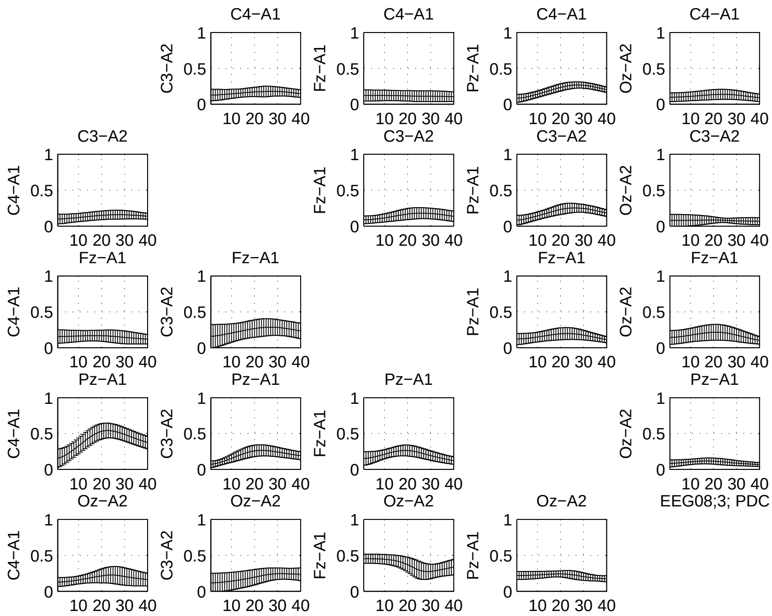

Figure 82: PDC as in (10): Condition #3 and EEG08. *X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

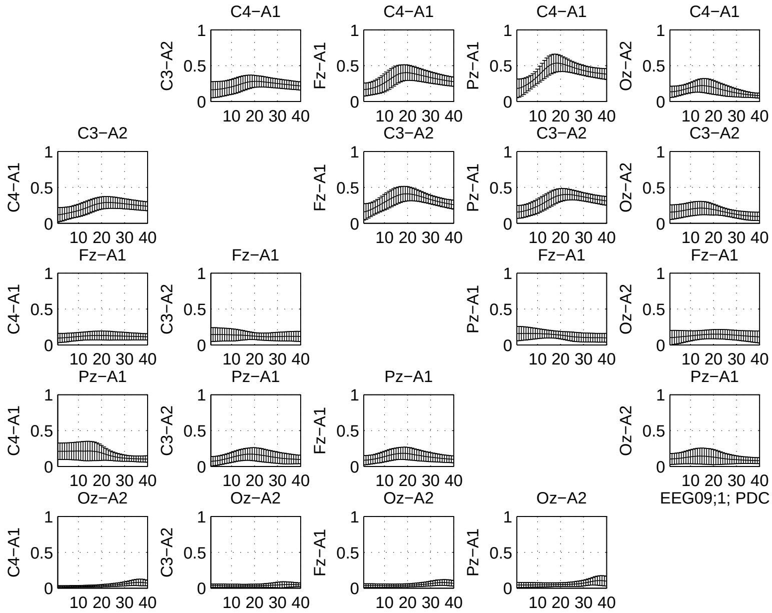

Figure 83: PDC as in (10): Condition #1 and EEG09.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

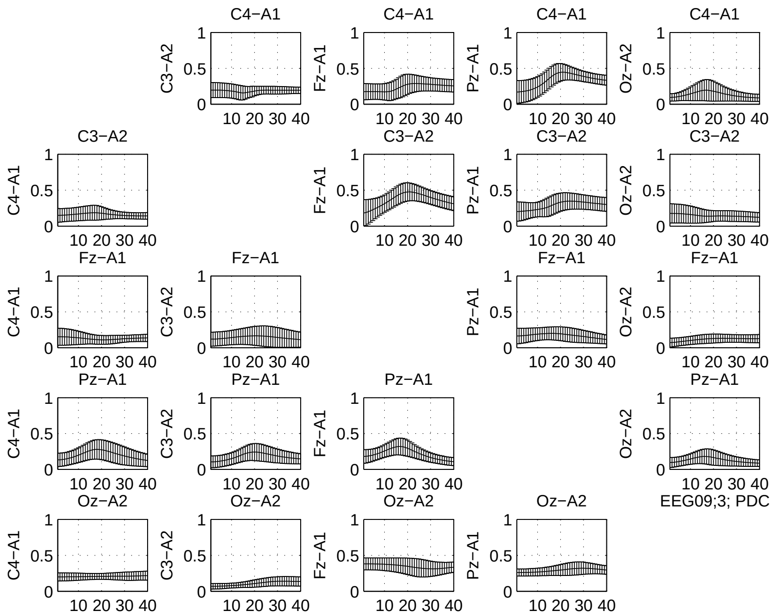

Figure 84: PDC as in (10): Condition #3 and EEG09.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

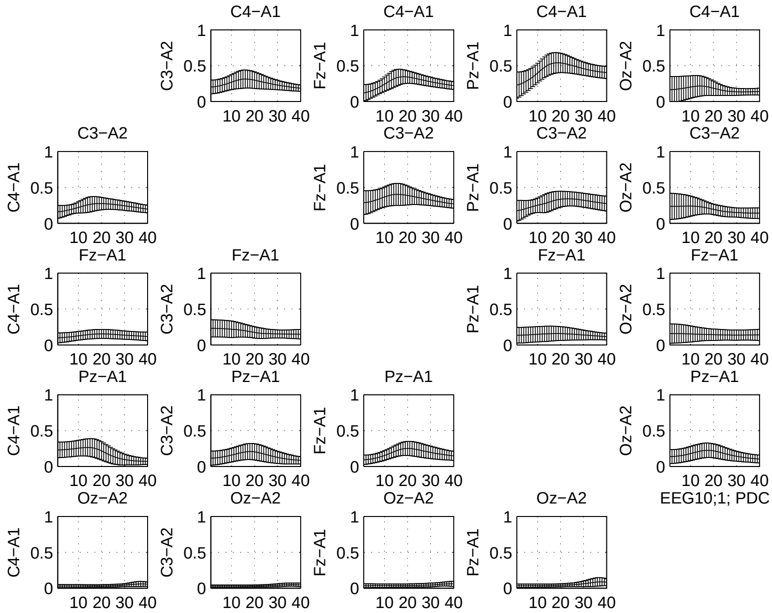

Figure 85: PDC as in (10): Condition #1 and EEG10.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

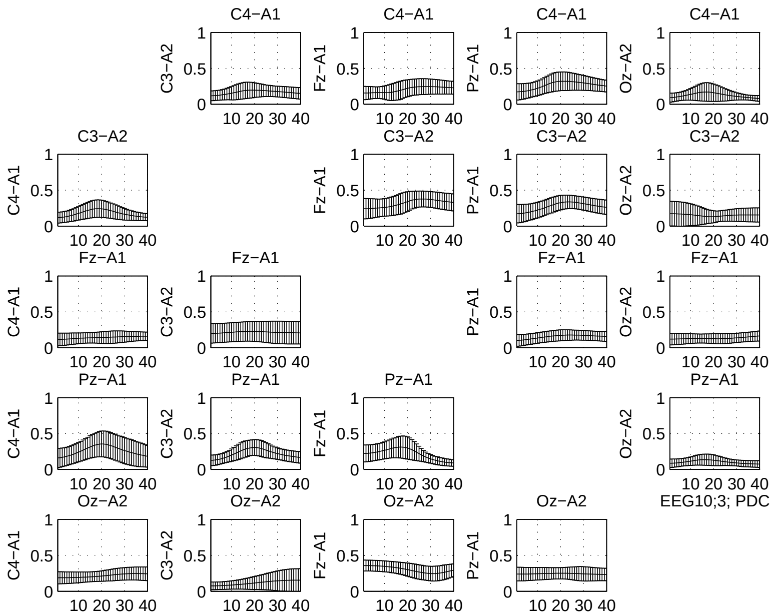

Figure 86: PDC as in (10): Condition #3 and EEG10.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

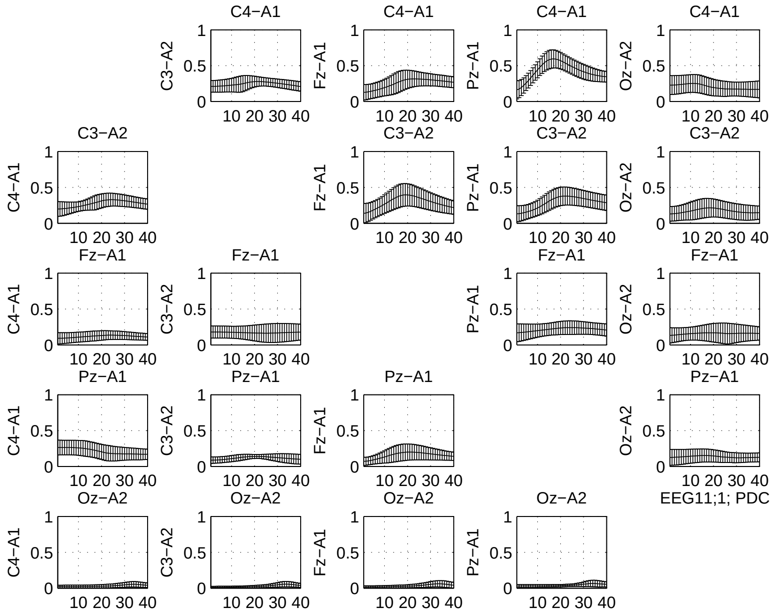

Figure 87: PDC as in (10): Condition #1 and EEG11.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

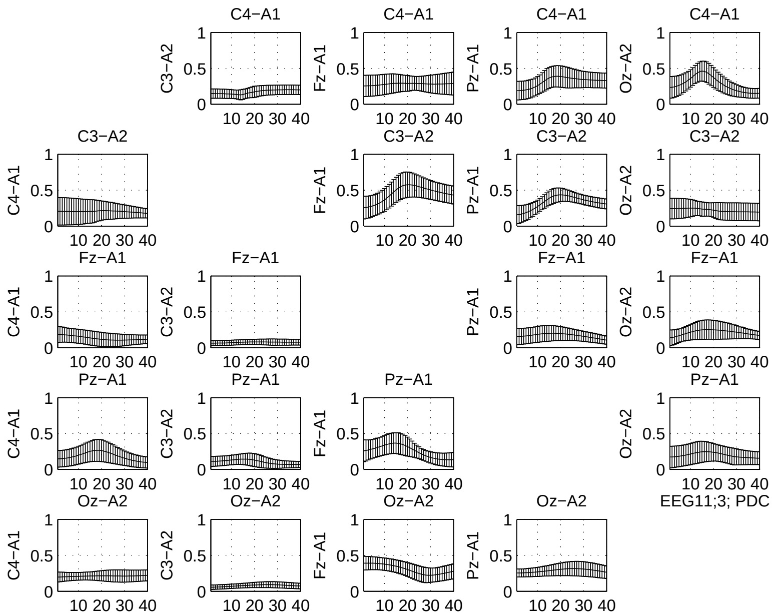

Figure 88: PDC as in (10): Condition #3 and EEG11.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

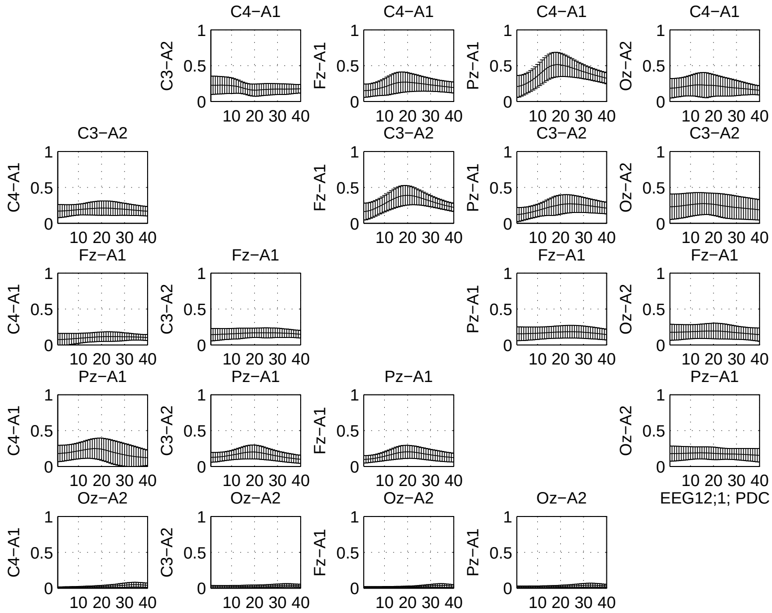

Figure 89: PDC as in (10): Condition #1 and EEG12.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

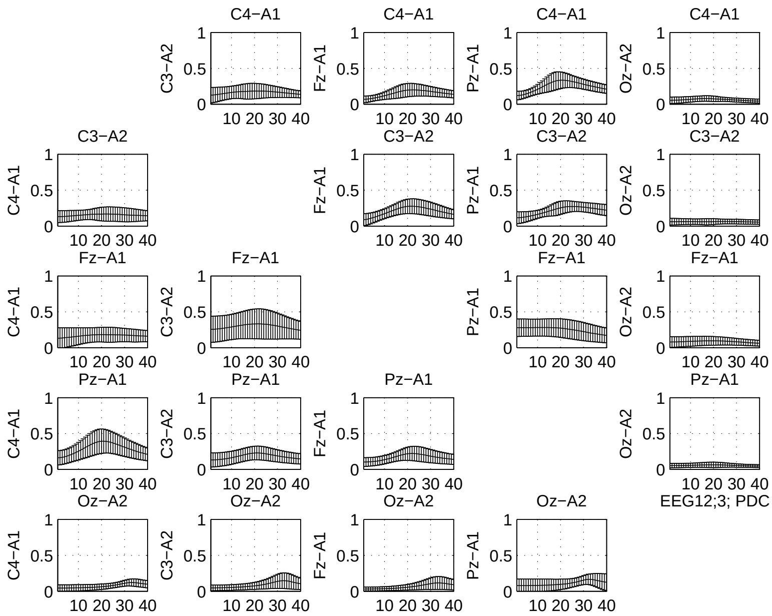

Figure 90: PDC as in (10): Condition #3 and EEG12.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

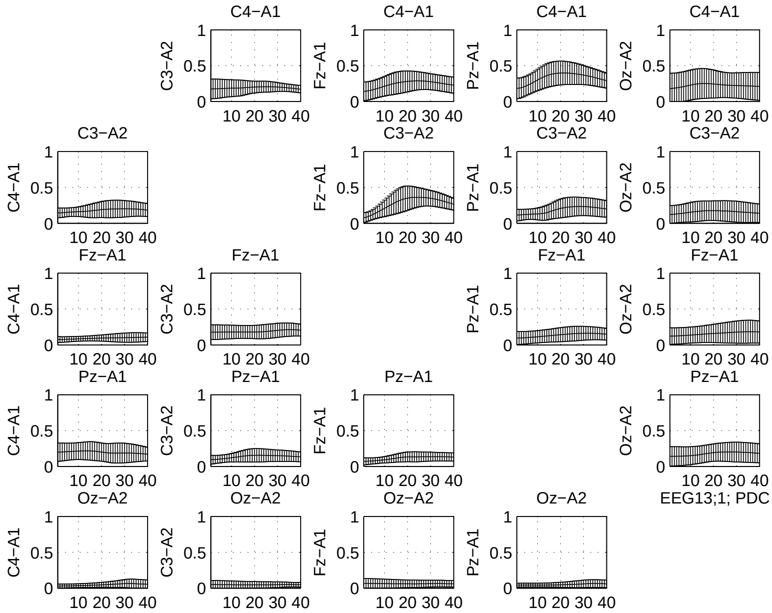

Figure 91: PDC as in (10): Condition #1 and EEG13.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

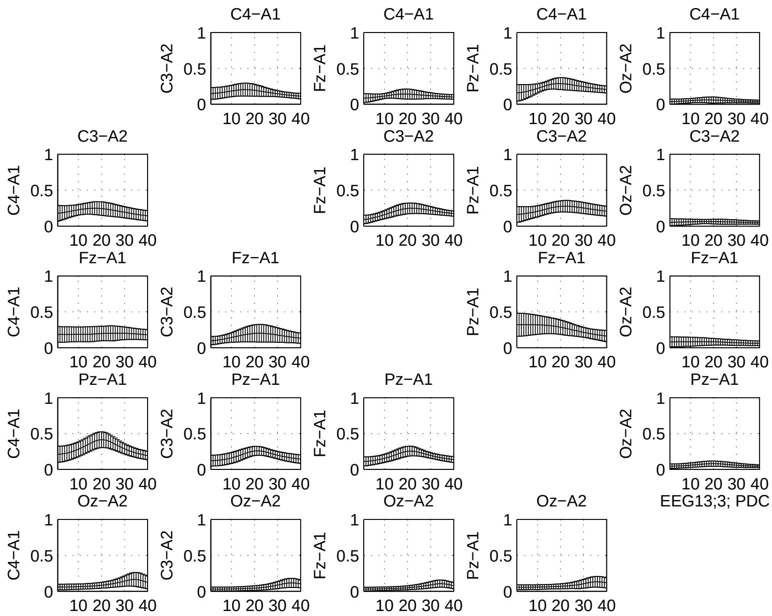

Figure 92: PDC as in (10): Condition #3 and EEG13.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

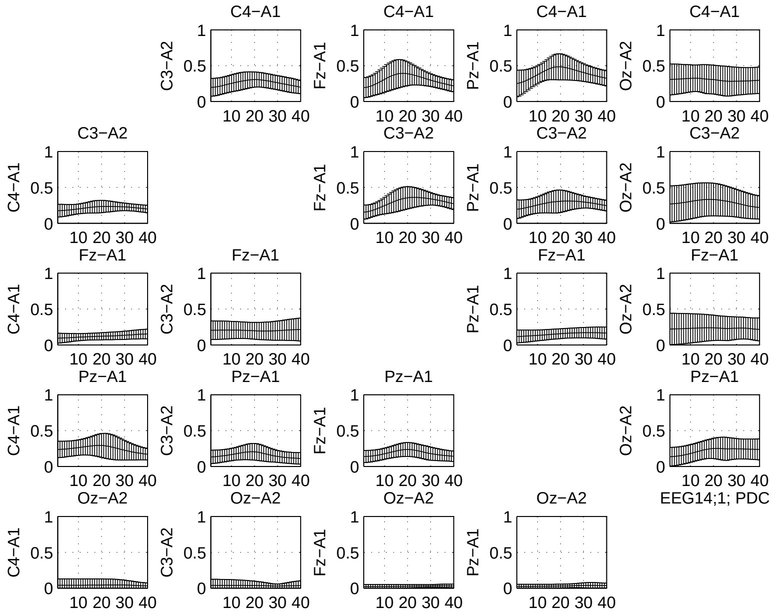

Figure 93: PDC as in (10): Condition #1 and EEG14.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

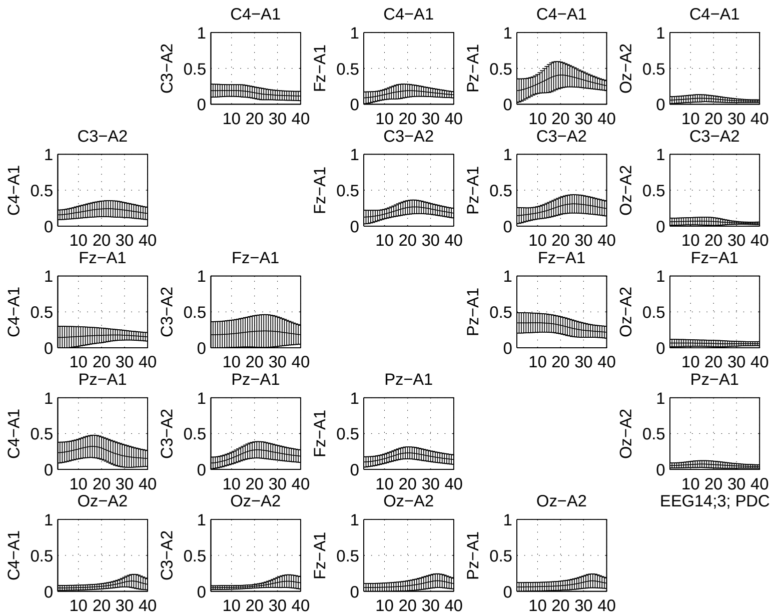

Figure 94: PDC as in (10): Condition #3 and EEG14.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

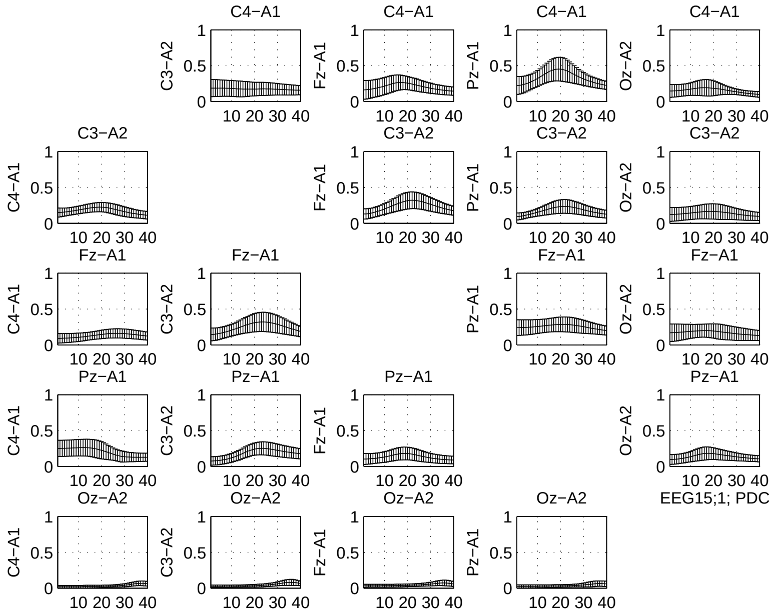

Figure 95: PDC as in (10): Condition #1 and EEG15.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

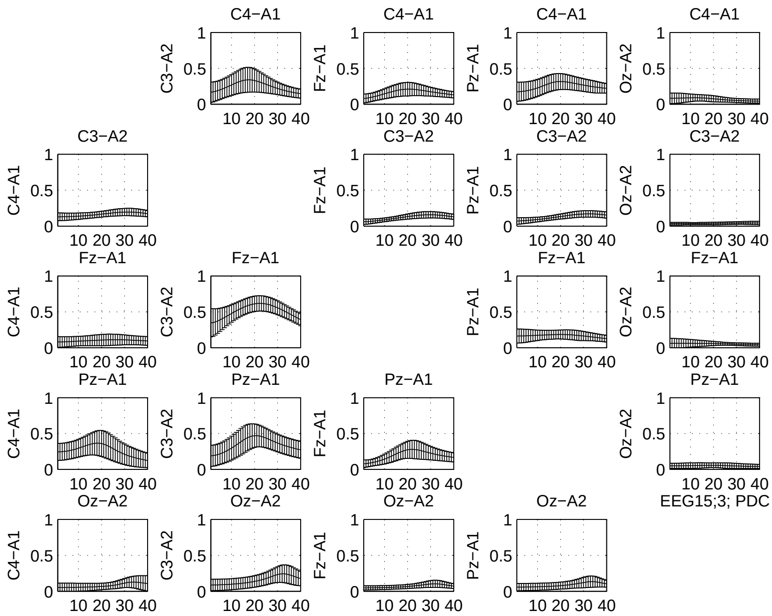

Figure 96: PDC as in (10): Condition #3 and EEG15.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

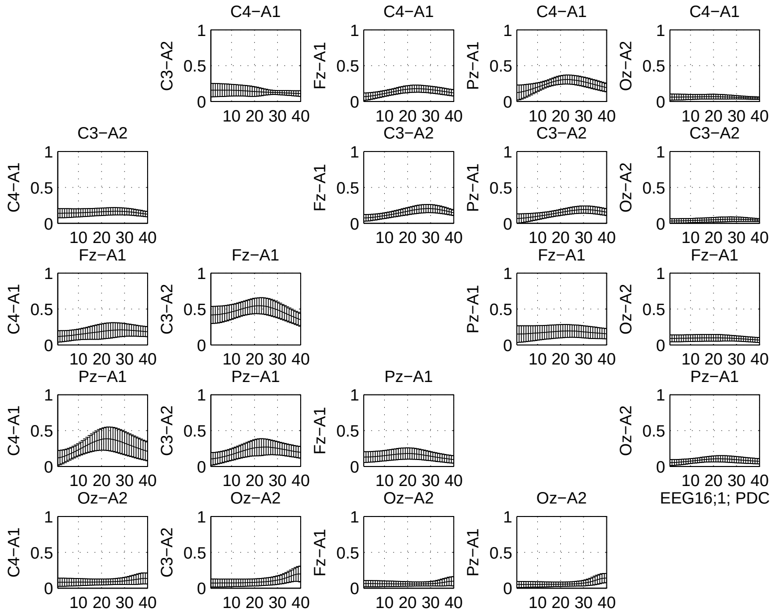

Figure 97: PDC as in (10): Condition #1 and EEG16.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

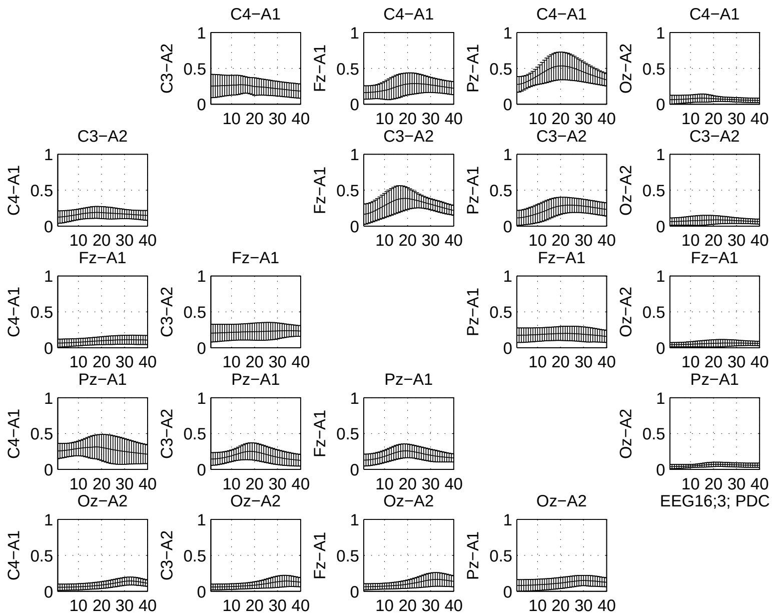

Figure 98: PDC as in (10): Condition #3 and EEG16.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

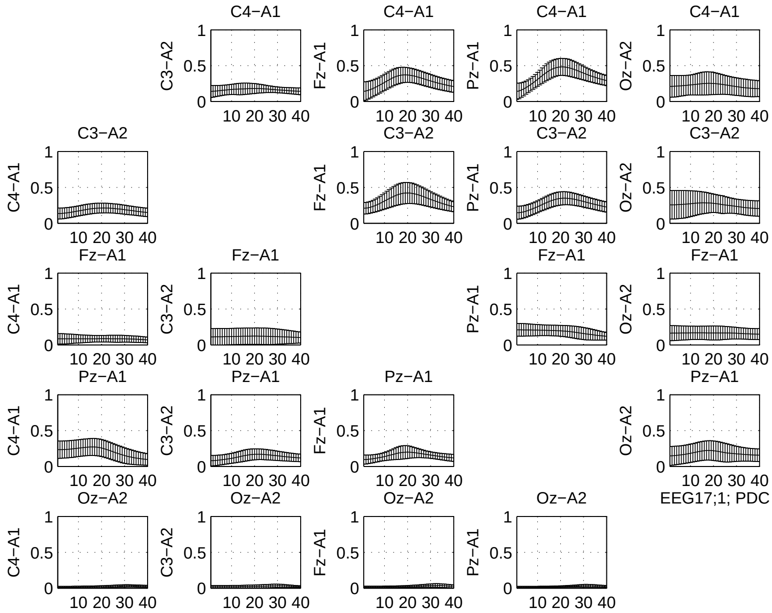

Figure 99: PDC as in (10): Condition #1 and EEG17.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

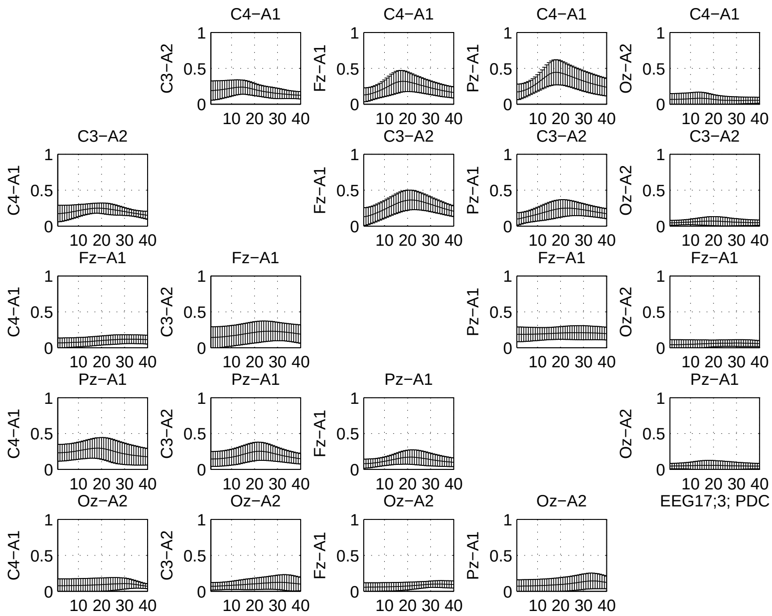

Figure 100: PDC as in (10): Condition #3 and EEG17.*X-axes* in all plots are frequencies $0-20$Hz (DC and frequencies around 1Hz are usually filtered by EMD thus no activity there analyzed).

4 Future work

4.1 Statistical analysis of synchrony patterns

Confidence levels of synchrony "patterns" in around 20Hz and around 70Hz to be analyzed.

4.2 Automatic classification/recognition based on synchrony patterns

4.2.1 Two classes of *no-nap* and *40 minute nap* conditions

4.2.2 Trial of clustering/classification of test batteries 8 to 17

References

[1] K. J. Friston, "Modalities, Modes, and Models in Functional Neuroimaging," *Science*, vol. 326, no. 5951, pp. 399–403, 2009.

[2] T. M. Rutkowski, A. Cichocki, and D. P. Mandic, "Analysis of brain responses to musical, steady-state auditory and environmental noise stimuli - A BMI feature extraction approach," *Neurocience Research*, vol. 61, no. 1, Suplement 1, p. S252, 2008.

[3] T. M. Rutkowski, D. P. Mandic, A. Cichocki, and A. W. Przybyszewski, "EMD approach to multichannel EEG data - the amplitude and phase synchrony analysis technique," in *Advanced Intelligent Computing Theories and Applications With Aspects of Theoretical and Methodological Issues Fourth International Conference on Intelligent Computing, ICIC 2008 Shanghai, China, September 15-18, 2008 Proceedings* (D.-S. Huang, D. Wunsch II, D. Levine, and K.-H. Jo, eds.), vol. 5226 of *Lecture Notes in Computer Science*, pp. 122–129, Springer-Verlag Berlin Heidelberg, 2008.

[4] T. M. Rutkowski, A. Cichocki, T. Tanaka, A. L. Ralescu, and D. P. Mandic, "Clustering of spectral patterns based on EMD components of EEG channels with applications to neurophysiological signals separation," in *Advances in Neuro-Information Processing* (M. Köppen, N. Kasabov, and G. Coghill, eds.), vol. 5506 of *Lecture Notes in Computer Science*, pp. 453–460, Springer, 2009.

[5] T. M. Rutkowski, A. Cichocki, T. Tanaka, D. P. Mandic, J. Cao, and A. L. Ralescu, "Multichannel spectral pattern separation - an EEG processing appli-

cation," in *Proceedings of the 2009 IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP2009)*, pp. 373–376, IEEE, 2009.

[6] T. M. Rutkowski, D. P. Mandic, T. Tanaka, A. Cichocki, D. Erickson, and J. Cao, "Interactive components extraction from fEEG and fNIRS for affective brain machine interfacing paradigms," *Computers in Human Behavior*, pp. (tba, in press), 2009.

[7] M. Kaminski and K. Blinowska, "A new method of the description of the information flow in the brain structures," *Biological Cybernetics*, vol. 65, no. 3, pp. 203–210, 1991.

[8] E. Pereda, R. Q. Quiroga, and J. Bhattacharya, "Nonlinear multivariate analysis of neurophysiological signals," *Progress in Neurobiology*, vol. 77, no. 1-2, pp. 1 – 37, 2005.